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CHAINS OF FUNCTION DELIVERY:
A ROLE FOR PRODUCT ARCHITECTURE IN CONCEPT DESIGN

by

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B.S., Mechanical Engineering
The University of Texas at Austin, 1990

S.M., Mechanical Engineering
Massachusetts Institute of Technology, 1996

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY IN MECHANICAL ENGINEERING
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CHAINS OF FUNCTION DELIVERY: A ROLE FOR PRODUCT ARCHITECTURE IN CONCEPT DESIGN

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TIMOTHY W. CUNNINGHAM

Submitted to the Department of Mechanical Engineering
on January 9, 1998 in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy in Mechanical Engineering

This research intends to improve three areas of team performance in concept design: the team's understanding and recognition of the product architecture, the team's ability to document integration issues and risks, and the team's ability to judge whether a product concept is worthy of further pursuit. Many of the high-impact decisions made in concept design revolve around integration issues: how the product's physical elements work together to deliver the performance characteristics, or functions. The product architecture, a singularly important characteristic of the product, is in great part determined by the mapping of the product's functions to the physical elements that deliver those functions. Integration issues pose a unique kind of integration risk: the chance that adequately designed individual elements will not function properly when connected to form the product, or cannot be assembled and debugged easily and quickly. During concept design, a development team must recognize integration issues in the functional-physical mapping so they can assess the associated integration risk, and judge their concepts on this basis. Since information is weak and fragmented during concept design, performing a formal analysis of the problem is a significant challenge.

In addressing this problem, the thesis begins with an explanation of the conflicts between the design theory representations of how architecture is created and real issues faced in product development. Specifically, many decisions encountered by a multi-disciplinary development team are made in the physical domain and influence the decomposition, altering the functional-physical mapping. Because the theory does not allow for physical decomposition, this part of the mapping goes undetected in current approaches. Integration issues and conflicts often result. This thesis expands the current theory by creating a framework for architecture that allows for decomposition choices of this type.

Given this theoretical framework, two themes are explored. First, a systematic procedure for identifying integration issues in mechanical assemblies is developed. The procedure captures chains: graphical representations of how product-level attributes are delivered, depicted on a hierarchy of the physical elements. Chains, which differ for each concept and decomposition, show 1) which functions are delivered in integral fashion, and 2) which elements play a role in delivering each function. Represented graphically, chains can help the multi-disciplinary team relate the diverse technical and non-technical influences on decomposition and architecture. Metrics can then be applied to reveal the integration issues and integration risk associated with

many, potentially conflicting chains. The research applies established part locating mathematics in the procedure, expanding the utility of this existing idea by applying it to concept design. Second, the thesis develops a method for conducting a chain analysis of candidate concepts and decompositions, creating a framework for trade-offs in the context of architecture. The method and chain procedure and metrics are tested on a real, complex, integral product, the Lockheed Martin Joint Strike Fighter military aircraft, to assess their utility.

Thesis Supervisor: Dr. Daniel E. Whitney
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BIOGRAPHICAL NOTE

Timothy W. Cunningham
Captain, United States Air Force

22 January 1968	Born, Miami, FL
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Integrated Product Development
Integrated Product Teams
Systems Engineering
Product Architecture
Supply Chain Design
Assembly Modeling
CAD
Manufacturing Processes

Publications

Cunningham, T.W., "Chains of Function Delivery: A Role for Product Architecture in Concept Design", unpublished MIT Mechanical Engineering Ph.D. Thesis, February 1998.

Cunningham, T.W. and Whitney, D.E., "The Chain Metrics Method for Establishing the Product Architecture During Concept Design", submitted to ASME DTM 1998.

Cunningham, T.W., Whitney, D.E., Quinn, M., and Schwemmin, R., "Chains of Dimensional Control: A Producibility Input During Concept Design", submitted to the Society of Automotive Engineers Aerospace Technology Conference, 1998.

Cunningham, T. W., Lee, D.J., Mantripragada, R., Thornton, A.C., and Whitney, D.E., "Definition, Analysis, and Planning of a Flexible Assembly System," Proceedings of the Japan/U.S.A. Symposium on Flexible Automation, ASME, June 1996.

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Cunningham, T. W., "Application of IBHVG2 for Predicting 60mm Gun Performance," WL-TR-93-7060 (DTIC), August 1993.

Aziz, S., Cunningham, T.W., and Moore-McCassey, M., "Design of an Unmanned, Reusable Vehicle Concept to De-orbit Debris in Earth Orbit," University of Texas ME Design Project, submitted to the National Aeronautic and Space Administration, December 1990.

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This is the last portion of the thesis I found myself writing, yet it is perhaps the most important because it encompasses so much about what attaining a Ph.D. is all about. I sat down with Dr. Joe Foster, my chief scientist in Florida, in 1993 to discuss my potential for earning a Ph.D. He explained to me what a Ph.D. is supposed to be: a person who defines the next set of important problems to be solved, and who defines a path toward a solution based on scientific fundamentals. Working for Dr. Foster, I learned not to fear new and unstructured problems, but to seek them.

When you recognize that the objective for attaining this degree is to learn to be an identifier of new problems and solutions, it puts a huge emphasis on the person who will be your mentor. I can not express in words what it has meant to me to have had the opportunity to work for Dr. Dan Whitney. He has exceeded every positive expectation I had for my advisor, and dismissed every negative. In every conversation we had, he sought to teach, to guide, and to expand my thinking. Yet, he never forced the agenda of this research, and because of that we both learned from the experience. This is a mix that I can only hope to learn when I fill his shoes for someone else, how to mentor while providing autonomy. Watching Dr. Whitney conduct his research has shown me that the Ph.D. requires that you go into all endeavors with an open mind and be forever the student.

I was also fortunate to have three additional faculty members on my committee who all think outside the normal bounds of disciplines and traditional product development thinking. Profs. Warren Seering, Steve Eppinger, and Charlie Fine all added to my progress. They too were a doctoral candidate's dream because they never forced their agenda on me, but instead all contributed important guidance to help me pursue my own path.

This research was successful because it was based on practical application. The majority of my experience in industry over the last two years was spent working with the Lockheed Martin Joint Strike Fighter team. As a group, I found them to be open minded, challenging, and hospitable in every way. I owe a huge debt of gratitude to Mr. Matt Quinn and Mr. Dale Wolf, who both dedicated time and effort to the maturation of my ideas toward practical thinking. Mr. Bill Bullock offered the company as a host, and Mr. Mike Packer and Mr. Guy Gordon helped me get launched. I would also like to thank Lt. Col. Earl Wyatt at the Government Joint Strike Fighter office for his support. I need to again thank the people at the Vought Center of Northrop-Grumman, especially Mr. Cartie Yzquierdo, who hosted the first phase of our research. Finally, Ford and Boeing also both supported our work.

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I shared an office with a lively and diverse group of officemates: Sloanies, TPPers, and a couple of engineers like me all in the cross-functional mix. Renata, Tariq, Rich, Mary Ann, Carlo, Don, Jeff, and Benoit all added to my experience. I want to thank my quals study group: Manuel Jim, and Gu. That was a miserable couple of months we spent together. Thanks to Krish for sharing the experience on the project and the assembly course.

I have received enormous support from my family. Without it, this thesis would never have been completed. I want to thank Mindy for sharing a wonderful time in the Boston area, and for her patience with the lengthy travel that accompanied this research. Thank you Amelia, who has only been with us the last year but has been a most welcome distraction. I want to thank the other Dr. Cunningham, my dad, for his advice, and my mom for infinite prayer and encouragement. My brother John, who almost threw me off track on this research, was also very timely with his support. My wife's parents were very supportive as well. My mother-in-law proofread this thesis, and my father-in-law broke the land speed record from Texas to Boston to get her here for that task.

I hope everyone who had a part in this feels a level of accomplishment, as this was a shared experience.

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1. Introduction

This chapter introduces the research, outlines the thesis, and provides guidance on how the reader should proceed. Section 1.1 motivates the topic by describing what an assembly integration problem is in the context of my early "shop floor" experience in this research. I use this story to introduce the idea of a chain and its communicative power. This research shows how the type of problem described in this story, which is common to many companies and many types of products, can be avoided by using chains in the early, concept phase of design. The two main themes of my research, related to chains and their use in concept design, are summarized in Section 1.2. Section 1.3 outlines the remaining seven chapters of the thesis. Section 1.4 explains how readers with varying levels of familiarity with the topic may wish to work through this material.

1.1 Example of an Integration Problem Encountered in Assembly

The first day I walked onto the floor of an airplane factory to begin this research at the Vought Aircraft Company, I recognized that companies involved in product development continue to need tools that help them solve problems requiring "integration." The need is clearly evident when one visits any product's assembly plant and recognizes the effort required to create working assemblies out of many individual parts. Often, when I have asked about first impressions of aircraft assembly, people recall being struck first by all the work that goes into fastening. It is something to behold - a little fastener every inch or so for hundreds of feet of structure, and the loud pounding of rivets. People have the same reaction in an automobile plant when the loud welding guns discharge and the sparks fly. They walk away thinking that "assembly" is "fastening."

Assembly is not just fastening, it is a physical realization of a much bigger issue faced in product development: *integration*. At this aircraft assembly plant, I was struck by all the effort required to achieve the dimensions of the finished product. I have personal experience with this type of problem, so I have learned that achieving tight dimensions accurately and repeatably is difficult. Success requires substantial formal and informal communication and coordination among many people. Communication like this is a mark of integration. The starting point of our research was to look for problems in assembly that could potentially be traced back to early phases of design indicating where proper integration did not occur.

Aircraft assemblers face a real extreme in terms of dimensional accuracy, where misalignments of a few hundredths of an inch over tens of feet could cause the performance of the system to

degrade noticeably. This means that tolerances in assembly are required to be less than one thousandth of an inch per inch. A great deal of large, dedicated equipment called "fixtures" is required to get the parts of the aircraft properly aligned, and hand labor is involved in correcting misalignments that do occur. Both fixtures and hand labor entail significant costs, both in terms of non-recurring cost to begin production and in terms of recurring cost of inefficiencies in the process. Misalignments that happen every time due to some unknown/uncorrected error require difficult corrective actions involving many people, and in some cases they are unable to solve this type of problem.

Vought hosted our research and permitted us to look at some of the more complicated problems that they were having trouble solving. In my case I looked at an assembly called a "nacelle" that houses the engines that hang under the wing of the C-17, a large Air Force transport aircraft that was still in early production.[1] I spent several days learning about one particular problem, plus the organization, the parts of the assembly, and how the parts are fabricated and assembled. I learned that a highly skilled floor worker basically dedicated all his time to fixing one particularly costly problem on each nacelle.

Dr. Whitney came for a visit after about 10 days and I started to describe another problem to him. The nacelle has a large set of "clamshell" doors (see Figure 1-1a) that give mechanics access

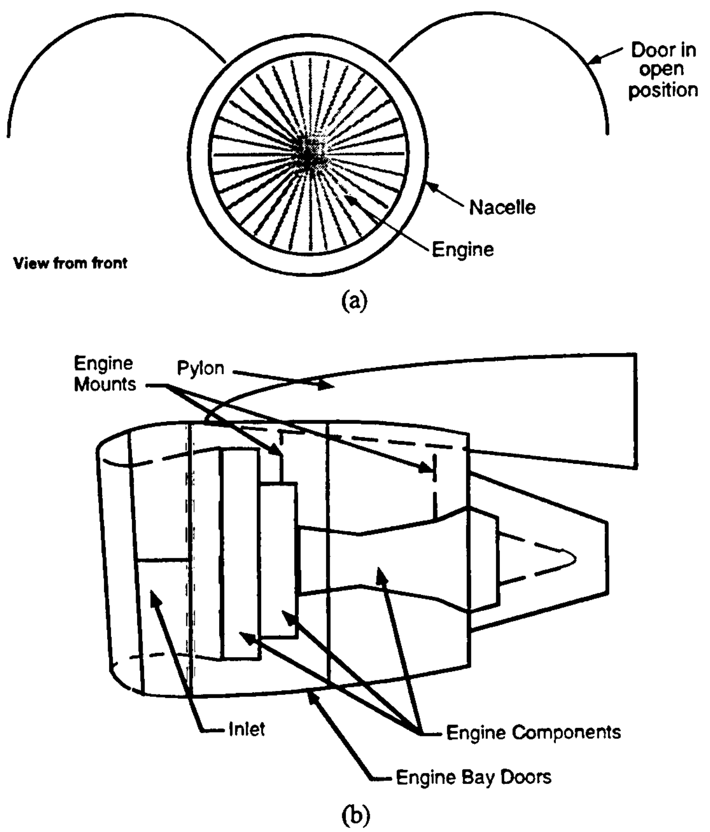


Figure 1-1. Schematics of the C-17 nacelle, (a) clamshell engine bay door operation, (b) component names.

[1] In about 6 years between initial production in 1989 and our research in 1994-1995, Vought shipped the nacelles for 12 aircraft. At four per aircraft they had built less than 50 overall, compared with approximately 200 as of this printing.

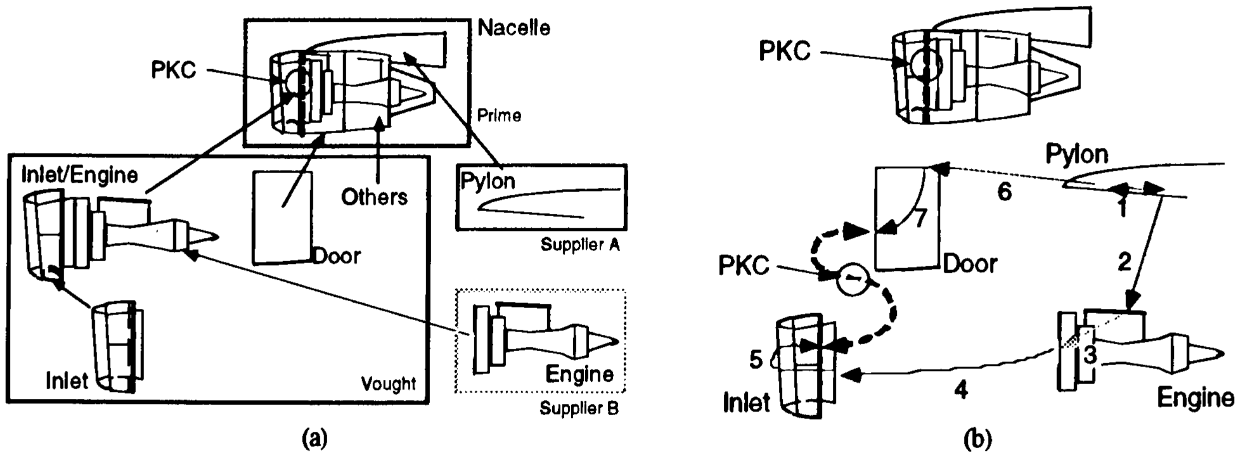
to the engine from below. Each door has to close onto a small surface on the assembly just forward of the door, called the inlet (see Figure 1b), and align very accurately with the skin of the inlet. The interface of the door to its resting surface on the inlet has to be accurate because the door doesn't connect to anything else, yet it must stay tightly closed in flight; also, the doors and inlets are all supposed to be interchangeable to make the airplane easy to repair. Vought was dedicated a good deal of effort to this "gaps" issue over the entire nacelle. The inlet/door gap was one of many that needed to be controlled but with which they were still struggling to produce repeatedly without a lot of detailed hand labor.

Instinctively from his experience in designing assemblies and processes, Dr. Whitney suggested that I draw him a picture of how the inlet/engine door gap was created. Our thinking here was to draw a tolerance chain, that is, to note all the dimensions that combine to affect this end dimension of interest. We were just making a sketch, not yet thinking about documenting these tolerances quantitatively. We just wanted to draw a picture so we could understand what might affect this gap. We pieced together what I had learned to that point: which companies made and assembled what, how these parts and assemblies were connected to each other, and when these decisions had been made. Figure 1-2 summarizes this information.

The result of this exercise is what I call a "chain": *a graphical representation of dimensional relationships that affect the final assembly-level dimension of interest, depicted on a hierarchy of the physical elements*. A chain in this context is a "low-tech" version of a tolerance chain that maintains the scientific basis of a tolerance chain to establish the content, but that we choose to populate with other information besides quantitative tolerance information. This thesis explains how this qualitative information is in fact more valuable because it allows us to analyze the problem at a higher level in the early design phases before the quantitative details are available or needed.

Figure 1-2a shows 1) a decomposition of the nacelle into its sub-assemblies; 2) the supplier of each: Prime, Vought, Supplier A, or Supplier B; and 3) the dimension of interest, labeled "PKC." Figure 1-2b shows the chain for this PKC depicted on the images of the sub-assemblies. The chain is a graphical representation of seven dimensions that combine to affect the end dimension - the gap that was not being delivered repeatedly. The seven dimensions are called "links." A chain is documented by following a few simple principles about how parts become fixed relative to each other as they are attached (described in Chapter 4). Some of these links are in individual parts, some are in fixtures, and some are in reality a representation of a set of several dimensions, some in parts and some in fixtures. These dimensions are in four different elements of the nacelle (including the engine and the pylon that attaches to the wing) and in three connections between these different elements. The picture looks a lot like one Dr. Whitney and I drew in a notebook that day on the factory floor. Figure 1-2c lists some details about the links. All the effort depicted in this chain, dispersed among many stages of the process and many suppliers, is required just to repeatably achieve one seemingly simple gap.

No one had the information contained in Figure 1-2 in one place. I had to piece it together based on what I had learned from several fragmented sources. Dr. Whitney and I drew the chain as we



Link	Description	delivered in	supplier	technology
1	Relative position of the engine and door attach points	pylon assembly	supplier A	fixtured, and many assembly steps
2	Attachment of engine lugs to pylon	final assembly	prime	interchangeable lugs
3	Relative position of inlet attach ring in engine and engine lugs	engine assembly	supplier B	multiple mechanical assembly steps
4	Attachment of inlet to engine	inlet/engine mate	Vought assembly	matched holes
5	Relative position of skin edge to engine attach ring in inlet	inlet assembly	Vought assembly	fixtured, and many assembly steps
6	Attachment of door to pylon	final assembly	prime	interchangeable hinges
7	Relative position of forward door edge to hinges in door	fabrication	Vought fabrication	composite lay-up

(c)

Figure 1-2. Nacelle (a) decomposition and supply chain, (b) Inlet to Engine Bay Door chain, and (c) a corresponding list describing the attributes of the links.

walked over several thousand square feet of the factory. More questions arose as we went along, and we found the answers one by one. We could not physically touch all the links in this chain because some of the assemblies that affect this dimension were not built at Vought (engines and pylons). Vought is never sent the pylon, they just ship their assemblies to final assembly at another company and get word back about whether or not the gaps were acceptable.

The chain shows that Vought does not control all the contributors to the PKC. Though Vought is responsible for this gap, they only control three of the seven links. Vought can not solve the problem alone. To the person in charge of any one of the factory's assembly stations that Dr. Whitney and I traversed, just documenting this chain would have required a great deal of dedication. The team overseeing corrective actions for the gaps was following a systematic plan and method, had additional measurements taken on many different parts like the doors and inlet skins, and were analyzing the problem from several points of view. In the end though, this chain included types of information that was not readily accessible to this team because some of it was outside their control. Our drawing sparked interest as it packed important information into a small package. In the end I studied this problem in detail and compared corrective actions

methods at Vought with those at the Ford Motor Company in my master's thesis, including how the information in chains like this could improve both companies' corrective action processes [Cunningham].

The combination of the three parts of Figure 1-2 tell the story of this thesis in a nutshell:

- several physical elements of a product all have to work together for the product to function properly
- a great deal of information about these elements is needed to ensure that they will all come together as expected
- the information is produced in decisions made by many people, from many places and disciplines
- the decisions are made very early in the development process.

Each of these points raises key issues. First, there are functions that a product performs that are affected by many physical elements. *Product architecture* is the name now given to the scheme by which functions are assigned to physical elements and the interactions between those elements are defined. Every product has an architecture. Architectures are said to differ in the degree to which they are *integral* or *modular*. In a modular product, each function is mapped to one or a few physical elements. Modular products are attractive for a number of producibility and outsourcing reasons because the individual modules can be designed and made somewhat independently. In an integral product, one or more functions may share physical elements or many physical elements may work together to deliver a function. I call such functions *integral characteristics*. Integral products are also attractive for a number of performance reasons, such as weight or energy consumption.

Along with integral characteristics comes what we call *integration risk*: the risk that apparently properly made elements will not function as desired when assembled, or will require long error correction or adjustment. Integration risk rapidly spawns cost and schedule risk because integration problems are usually found late in product development, are hard to diagnose, and are the result of decisions related to architecture that are too difficult to change even if the problem is diagnosed. During concept design, it is incumbent upon a design team to recognize integral characteristics and associated integration risk, and judge their designs on this basis, before making commitments that will force them to deal with these issues for the remainder of the development program. So integration risk must be found early and be managed actively, but this requires identification of the architecture.

Second, a great deal of information is needed to communicate about the integral characteristics, and this information results from decisions made by many technical and non-technical people. While everything I discuss in this thesis is in the context of mechanical assembly, integration is equally a technical and non-technical problem. It is equal part design, manufacturing, assembly, strategy, organization, technology, etc. Empirical evidence shows that integration problems pose a challenge even in companies and programs that utilize the most advanced teaming arrangements and computer-aided design (CAD) tools. because this type of integrative information is not emphasized. The members of the team are often not capable of identifying the integration

problems based just on their experience. And, 3D CAD tends to focus more on parts and less on the integration of parts into working assemblies. All this has to be thought through together for integration to occur. Chains have proven to have a communicative capability in depicting this variety of information in a central, graphical, image.

Third, most of the decisions that lead to the integral character in an architecture are made in the early, concept phase of product development. The chain in Figure 1-2, documented in 1994, is in the main based on decisions made in the early to mid 1980s. These decisions include the decomposition that created the basic structure of the chain, the assembly planning that created the detailed places where the links stop and start, the processes used for each link, the suppliers of each link, etc. These decisions were made about 5 years before there was even a detailed design of the nacelle (so whether this product was designed on paper or in a CAD system makes no difference). Concept design is the phase where most of the cost of the product is determined, but the information available to assess the design is so weak or fragmented that it is extremely difficult to understand the effects of any single decision. In concept design it is nevertheless very important to understand the integration issues of the architecture and whether these pose integration risk. In the context of the C-17 example, I postulate that the ability to document the inlet/door gap chain when its structure was created, understand the effects that these technical and non-technical decisions were having on the chain's complexity, and use this and other chains to make trade-offs among different decisions before commitments were made, would have allowed the team to avoid this integration issue, or at least to have recognized it, brought it into control more easily, or made it possible for Vought to solve it.

Therefore, this thesis is about improving concept design as a source of competitive advantage for product development firms. This thesis intends to improve three areas of team performance in concept design: the team's understanding and recognition of the product architecture, the team's ability to document the integration issues and risks, and the team's ability to judge whether a product concept is adequate for further pursuit. This thesis uses chains to document the architecture, which makes the process systematic and therefore repeatable, and represents chains simply and graphically so a cross-functional team can understand the architecture together. The resulting chain documentation can be used later to analyze tolerances, plan assembly, and diagnose integration problems. This information is currently poorly documented or largely missing at many companies. This thesis develops useful metrics we can apply to chains before the details are available so that a design team can compare different architectures. Along the way, I define terms that advance the understanding of architecture and a method that expands how design theory reflects integration issues. This thesis develops a framework for the multi-disciplinary design team environment to apply chains and the metrics to different decompositions and understand the many decisions in the single context of architecture. All of these concepts are applied to real case studies and examples.

1.2 Formal Statement of the Research Themes

Three major lessons are captured in the C-17 nacelle story:

1. Producing a physical dimension like the inlet/engine door gap is harder than producing any one physical dimension on one part or in one assembly. These *physical dimensions*, and the

functions they affect, *are delivered in chains* of parts, assemblies, fixtures, and suppliers. Successful integration becomes less certain when the chain contains more physical elements and interactions among elements, more companies responsible for the links, and uncertainty about the capability of achieving any one link. This unique kind of integration risk demands special attention in product development because integration problems present the team with its most difficult challenges.

2. The chain as an illustration, a "low-tech" version of a tolerance chain, was very useful in capturing information that no one technical or non-technical member of the team had. Whether they were engineers, supplier managers, shop floor supervisors, assembly workers, at Vought or another company, etc., all share a larger role that is not communicated to them without some type of tool like chains. A simple chain picture explained this larger role to each of them. The underlying technical reasoning is critical, but the illustrative display is what may be most illuminating in this team environment. In this case and others, I have found that chains are able to communicate complicated problems in a simple, compact format.
3. Many of the decisions that affect a chain are made years in advance of detail design and production, very early in development. Back in the concept design phase, the lead design firm of the C-17 chose the basic "decomposition" of the nacelle into the pylon and pieces of the nacelle, and who would make them. Before detail design, Vought made plans of how their pieces would be connected, how the parts would be aligned to each other, etc., and what parts they would make or buy from suppliers. All of these decisions led to the complexity involved in the current problem. The problem could have been analyzed at a high level before detail design was even initiated.

I pursued the three interrelated lessons from the C-17 example in the context of mechanical assembly along two research themes:

1. The main structure of chains can be identified during concept design to plan the degree of integrality and integration risk in the product. Chains provide a means to estimate the different degrees of integration in different decompositions of candidate concept designs. And, these chains can be assessed to obtain early insight into integration risk. A systematic procedure is needed that describes how to capture and assess chains in concept design, when little about the product is formally defined. I pursued a diverse literature review including 1) design theory and systems engineering literature that model the process by which the product architecture is established, 2) management literature that relates broader strategic issues decisions to architecture, and 3) assembly modeling literature that establishes the underlying tolerance chain basis of the graphical chains to be used here. From this I developed a procedure and metrics for capturing and assessing chains during concept design, and demonstrated them in several examples.
2. Chains provide a systematic framework around which to develop a cross-functional team method for assessing the architecture, planning the level of integration, and estimating the integration risk. Recognizing that design, producibility, and strategic decisions impact the decomposition, and hence the chains, I developed a method to enable a chain analysis to be carried out by a design team during concept design. I developed a framework that shows how

to integrate (in the context of chains) the design, producibility, and strategy decisions that influence architecture . I demonstrated this in an in-depth case study.

Chains have an established mathematical and modeling basis developed in previous mechanical assembly research. This research focused on the application of chains in concept design. This work is limited to product functions that are affected by physical dimensions of the product. However, this limitation leaves a broad range of applicability as it includes numerous mechanical functions and selected functions in a variety of electrical and optical products. A natural extension of the work will be to mechanize the same concept design framework for development of products that operate in other domains.

1.3 Thesis Overview

Figure 1-3 shows the product of the thesis, a method for using chains in concept design to support architecture analysis and trade-offs in the design team called the Chain Metrics Method (CMM). The method depicts the interactions of team members from design, producibility, and various strategy disciplines. The team, made up of members these three groups, has input to the decomposition of the product. The method leads the team through the architecture analysis of

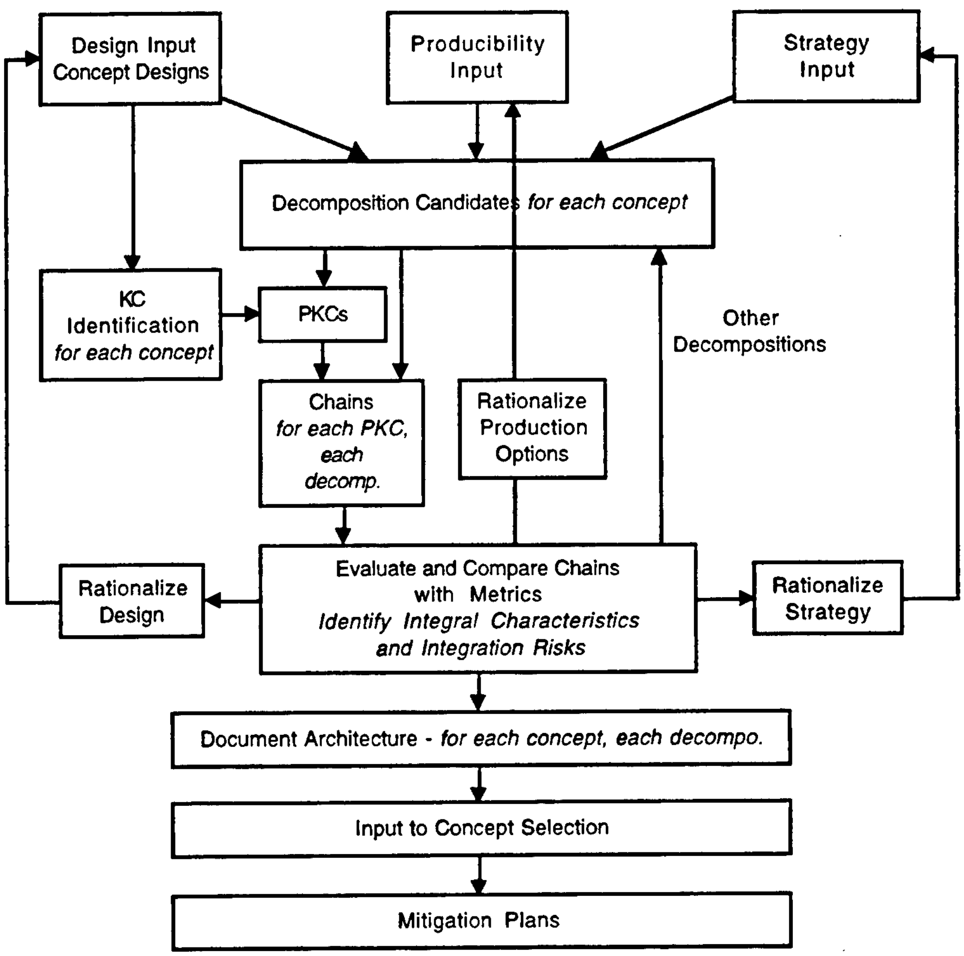


Figure 1-3. The Chain Metrics Method for architectural analysis during concept design with chains and metrics.

each candidate decomposition. In this analysis, integration issues are noted and conflicts between the desires of each group and the integration issues are recognized, noted as integration risks. Trade-offs occur through four types of iteration: consideration of other candidate decompositions, and trade-offs among the desires of the three disciplines based on the architectural insight gained.

Figure 1-4 shows part of a comprehensive case study I performed during the concept phase of the Joint Strike Fighter military aircraft product development program. This case study is described in detail in Chapter 7. Figure 1-4a shows the basic layout of the aircraft's structure, with the shaded components in the center representing the propulsion system. Figure 1-4b and 1-4c show two of the airframe decompositions analyzed in the course of the case study. Each decomposition has a different effect on the architecture, creating different integral characteristics and risks that the team must recognize. This case is an example of a highly complex architecture trade space among design, producibility, and strategic objectives. This complex problem required systematic analyses to help in the decision process when there was still sufficient flexibility to compare these different options but insufficient information available for a formal analysis.

Chapters 2 through 6 prepare the reader for this deep case study. Chapter 2 discusses the research methodology, development of the hypothesis, and the rationale for the examples and

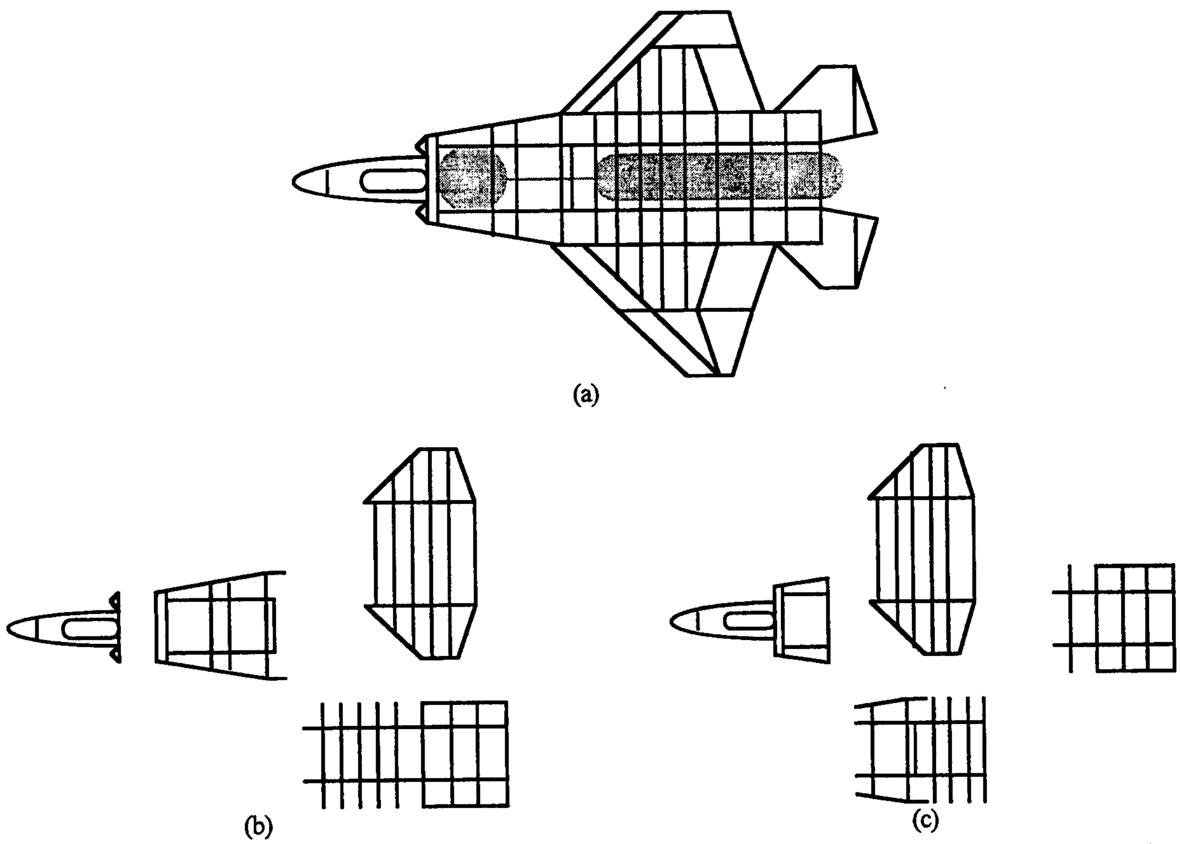


Figure 1-4. The deep case study described in Chapter 7, (a) the top view of one design concept, and (b) and (c) two candidate decompositions.

case study. The research was conducted as part of a larger project in which a major theme became the use of assembly modeling to focus design toward integration issues.

Chapter 3 is a review of the pertinent literature in design theory, systems engineering, product architecture, design for manufacturing and assembly (DFMA), and assembly modeling. The first three topics all represent in similar ways the two areas of focus here: how decomposition occurs, and how the functional-physical mapping that is the heart of architecture is determined. I discuss conflicts between real practice and the theory, and explain how my approach expands the representation of the theory to reflect real issues faced in product development.

My work is captured in the two right hand blocks of the matrix shown in Figure 1-5, which summarizes existing research and this thesis in a framework of architecture choices. Each square represents a combination of one or many functions delivered by one or many physical elements: two possibilities for each leading to four combinations. The way to read this figure is to look across each row. The top row deals with mapping of individual functions to the elements in physical space. The upper left box represents the possibility that the product will be designed so that each function is delivered by one or a few physical elements: this is the well-known extreme called the modular product. The upper right box represents the possibility that each function will be delivered by many physical elements working together: such a product will be said to contain one or more *integral characteristics*. A chains is used to depict the mapping of a function to the physical elements and their interactions. The second row deals with the mapping of many functions, which we must deal with in any product exhibiting a level of complexity of interest. The lower left box represents the possibility that several functions will be shared and delivered by one or a few physical elements: this is the well-known extreme called "function sharing." The lower right box represents a complex version of the one above it, wherein there are several integral characteristics shared in many of the same physical elements. The complexity arises in the all-too frequent situation where these characteristics conflict with each other. Chains can be used to describe this complex situation.

I claim that these two right hand boxes are under-represented in the literature, and therefore devote my work to developing our understanding of these complex, yet critical issues in product development. In words, this thesis focuses on making **architectural and decomposition decisions** (represented by **assembly design** issues) during **concept design**, and judging the **adequacy of those decisions** based on a number of **criteria related to integration risk**.

		Physical Elements	
Functional Requirements		One or a few	Many
	One delivered by:	Modular Characteristic	Integral Characteristic (chain)
	Many delivered and shared by the same:	Function Sharing	Coupled Integral Characteristics (coupled chains)

Figure 1-5. A matrix describing architecture choices. The focus of this research is on the two right hand blocks.

Chapter 3 also serves as an introduction to assembly models that form the basis for chains. This thesis does not develop the underlying theory and mathematics of chains. Instead, I apply this foundation in earlier phases of product development and different frameworks than it has been applied before.

Chapter 4 develops the principles for a systematic procedure followed to capture chains, rules for their representation, and metrics used to classify the integral characteristics and integration risks. The techniques developed in Chapter 4 are at the center of the CMM shown in Figure 1-3. First, the method is applied to a set of PKCs, derived from the Key Characteristics (KCs) of the concept. KC is a name for *a product attribute that most affects customer satisfaction, safety, or compliance with regulatory requirements*. The chain procedure captures all the relevant dimensional relationships in the decomposition for each PKC. Chapter 4 then develops a set of metrics to identify the integral characteristics and to assess the level of integration risk of each integral characteristic. Finally, Chapter 4 reviews how chains guide the use of quantitative variation analysis tools that are currently hamstrung because they require a large amount of information not generally available during concept design. In simplifying the use of these tools, chains lead the team to quantitative variation analysis much earlier than can currently be achieved.

Chapter 5 describes several examples of the use of the chain procedure and metrics. One of these examples is an automotive truck body characteristic that is delivered quite differently in each of two decompositions. Figure 1-6a shows a single stamped metal side body part with a few welded reinforcements for strength that includes both exterior and interior surfaces. The roof and floor are separate components. Figure 1-6b shows an alternative approach where the body is

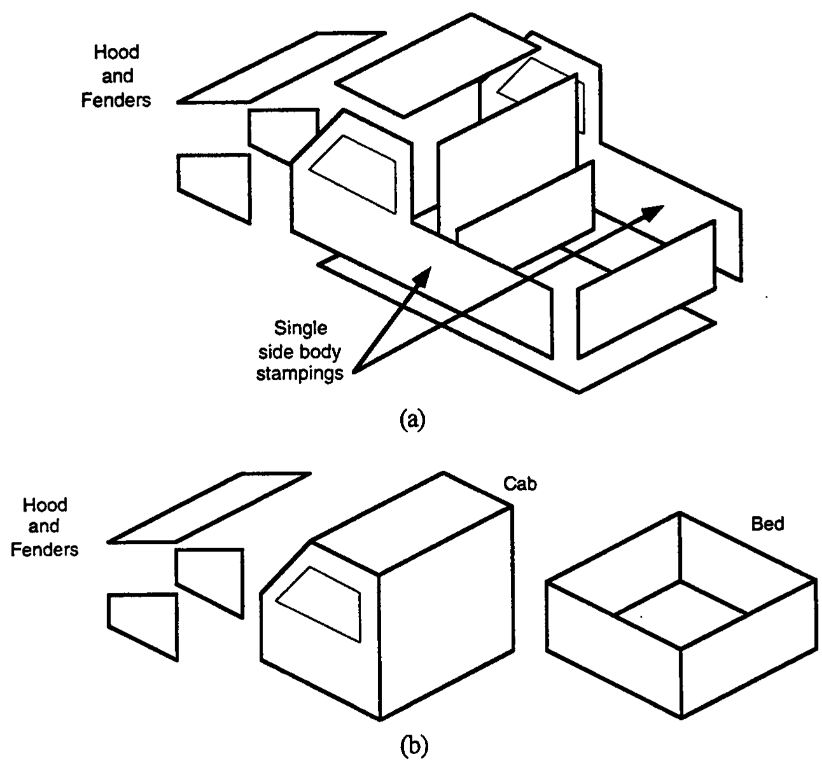


Figure 1-6. Two alternative automotive truck body decompositions.

decomposed into a cab and bed. Section 5.3 describes the strategic issues surrounding this trade-off, which are production driven. Other examples in Chapter 5 have decomposition options driven by other producibility and/or strategic factors with consequences on the architecture indicated explicitly by chains.

Chapter 6 explains the CMM in detail. It explains the roles each group plays in performing a systematic analysis of the architecture of each candidate concept and decomposition during concept design using chains and the metrics. Chapter 7 then applies the method to the JSF case study. Figure 1-7 shows schematically how each step of the method is applied to the case.

Chapter 8 concludes this thesis with four main topics. First, I assess the examples and case studies for fulfillment of the hypothesis and with comments from the company designing the JSF. Next, I discuss implementation issues in both commercial and defense product development. I then summarize the major contributions of my work. Finally, I make recommendations for future work in developing these ideas.

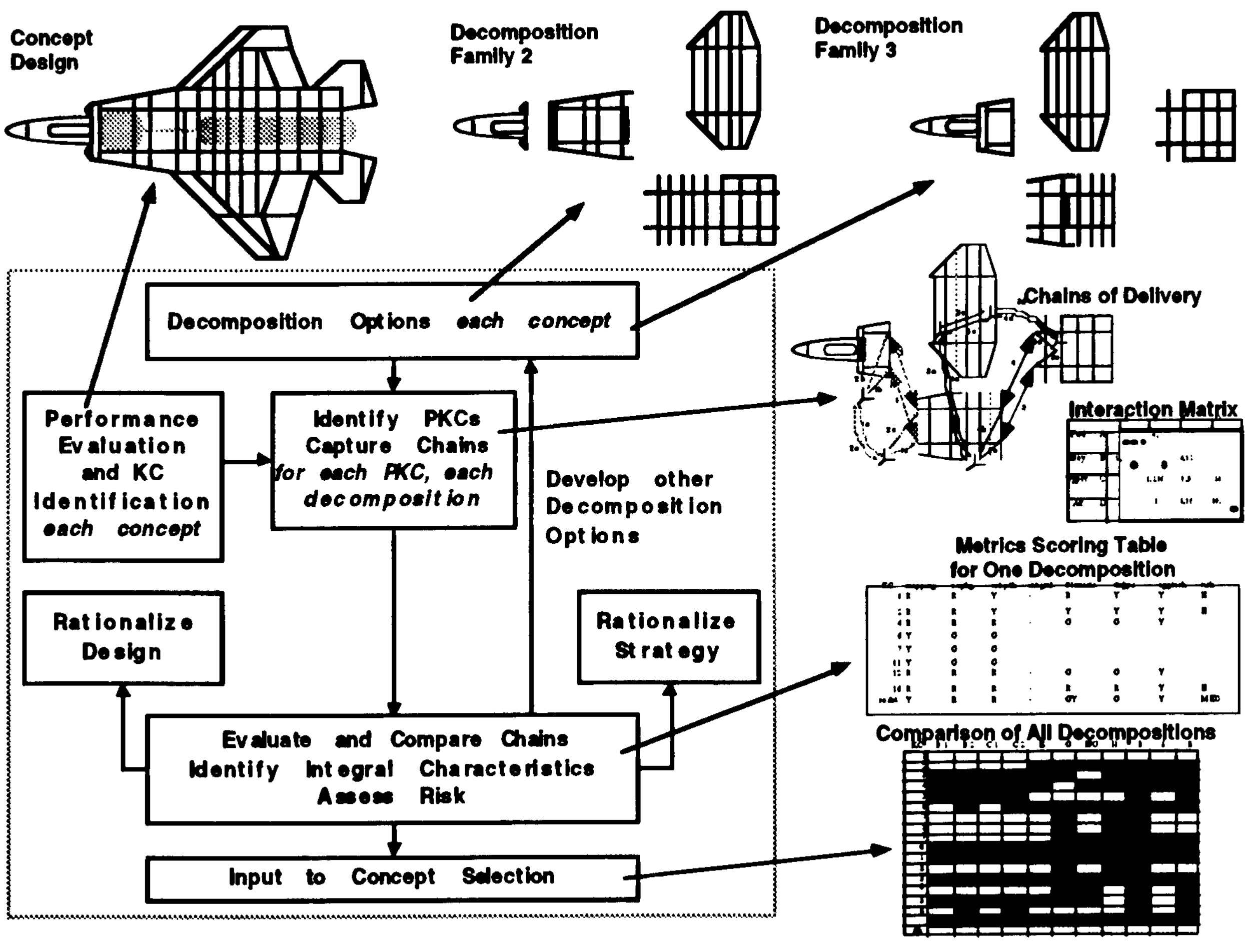


Figure 1-7. The relationship of the JSF case study to the CMM.

1.4 Road Map for the Reader

This thesis covers the topics introduced above in depth. Readers who are familiar with the topics can follow a relatively efficient path through this document. Readers who are interested in selected topics can proceed directly to the appropriate chapter. The following are specific recommendations:

- To focus solely on the documentation and assessment of chains, the reader should review the basis described in Section 3.3.3, the principles of the chain procedure and metrics in Sections 4.1 through 4.3, one or more of the examples of Chapter 5, the deep case study in Chapter 7, and issues associated with chains in Chapter 8.
- To focus on the broader issues of design methodology and product architecture, the reader should focus on Sections 3.1 and 3.2, the metrics of Section 4.3, the CMM described in Chapter 6, the deep case study in Chapter 7, and issues associated with design, product architecture, and implementation in Chapter 8.
- To review the conduct of this research, the reader should review Chapter 2 on the methodology, the discussion of the literature in Chapter 3, one or more of the examples of Chapter 5, the deep case study in Chapter 7, the summary and discussion of Chapter 8.
- For brief discussions of selected topics, review the list of anticipated publications in Section 8.1.

2. Research Overview

This chapter describes the research methodology. Section 2.1 describes the broader issues of research in product development, and some of the major efforts in this field at MIT that involve intensive interaction with industry. Section 2.2 summarizes the larger program in which this research was conducted. Specific focus is paid to a sub-group that investigated the use of mechanical assembly modeling methods early in product development. Section 2.3 discusses my research method in detail. This section describes the hypothesis, summarizes the literature I reviewed, discusses the case study and interviews conducted, and lists three evaluation methods. Section 2.4 explains how the research method is depicted in the remaining six chapters of this thesis.

2.1 Research in Product Development

Product development and Design Theory and Methodology (DTM) are active fields of research in academia that receive a great deal of attention from industry. The research, like product development itself, crosses academic disciplines and requires a broad view of technical, organizational, and managerial issues. Properly conducted research has immediate application in industry and offers competitive advantage to companies that apply proven results.

The attention paid to these fields of research is evident in recent research activities at MIT. This research project was conducted as part of a multi-disciplinary product development study called "Fast and Flexible Manufacturing in the Automotive and Aerospace Industries" (F&F). F&F was initiated in 1994 and involved deep case research on site at companies involved in product development and manufacturing. Our research project studied the integration issues associated with design and manufacture of complex assemblies in a dispersed supplier organization. The project involved engineering, management, and technology policy disciplines. Our efforts focused on the automotive and aerospace industries, which share many similar challenges. The project will be complete in May 1998 [F&F, Whitney et al 1995, Whitney 1998].

Two other large research efforts also influenced this research. First, beginning in the first year of our project, we began to interact with the "Lean Aircraft Initiative" (LAI). LAI is an Air Force sponsored program involving Government, the defense aerospace industry, and MIT to apply the appropriate principles of the lean manufacturing paradigm [Clark and Fujimoto, Womack et al, Womack and Jones] to defense aerospace product development and production [LAI]. In the last year, our project became affiliated with a much larger product development research effort involving many industrial sponsors and a broad set of academic disciplines. This effort is being

conducted by the new Center for Innovation in Product Development (CIPD) under a National Science Foundation (NSF) grant [CIPD].

Several overarching issues are being investigated in these research programs that are addressed specifically in this research, and are also called for in the findings of recent product development research [Finger and Dixon, Ulrich, several works of Eppinger, Whitney 1988 and 1990, Fine and Whitney, Burchill and Fine, Fine. etc.]. A few such research issues, my contribution, and the impact of this research are described in Table 2-1.

2.2 Fast and Flexible Program

The goal of the F&F Program is to improve the "first-time capability" in industry, i.e. the ability to deliver products that meet or exceed the anticipated quality, cost, and delivery schedule. The overarching hypothesis is that in current development processes, there is information missing from the design package that hinders communication in the dispersed supply chain, that in turn leads to reduced quality, excessive cost, or failure to meet the schedule. Early in the program we identified two major issues on which to focus:

- members of product development teams have a "part-centric" focus, i.e. they focus on their own part or component individually, and fail to appreciate how it interacts with other elements that make the product function as a whole; this was particularly revealed in how corrective actions were conducted when problems were encountered [Cunningham]
- a key type of missing information is that dealing with "interconnectivity", i.e. the design package has a great amount of detail regarding the geometry of every part, but includes little regarding how the parts form assemblies and function as a whole.

Table 2-1

Overarching Product Development Research Questions and My Contributions

Issue	My Contribution	Impact
70% of cost is determined during concept design	Concept design creates architecture, architecture inevitably contains some integral characteristics, and integration risk that results spawns cost, performance, and schedule risk	Improved ability to predict integration risk, cost avoided or at a minimum integration tasks planned and executed
Concept design needs strengthening, but accurate and detailed information is lacking	Key missing information relates to integration risk, and there is enough information during concept design to estimate integration risk because this information is inherent to the function-physical mapping and decomposition decisions made during that phase of product development	Improved focus on the critical issues - integration risk - and a process and metrics by which to evaluate it during concept design
Tools are needed to predict consequences of early decisions, relating to cost-performance- strategy tradeoffs	The Chain Metrics Method finds the integration levels and risks in alternate concepts related to delivery of Key Characteristics that are in turn traceable to product function	An agenda and roles of team members are defined for making these tradeoffs
Approach is needed for multi-discipline teams to communicate about diverse performance, producibility, and strategy issues	Chains are sufficiently non-technical that all disciplines can understand them but they are specific enough to support evaluation with metrics that represent the concerns of many team members	Improved communication among a diverse team that is traceable through all product development phases and relevant to downstream assembly planning tasks.

2.2.1 Program Characteristics

Our research approach had two characteristics. First, we performed deep case research of complex assemblies that we found to be indicative of problems faced in companies that are at the level of the state of the art in Integrated Product Development, Computer Aided Design, etc. There is a significant trade-off between deep case research and survey-based research. In the former, great depth can be investigated and problems can be followed to a high level of detail, but the risk is that the problems will be unique to a particular company or product. The latter approach allows for broad results, but can not be followed to sufficient depth to allow for the details to be revealed. As described below, I chose to perform deep case research, but to aggressively present my results to a wide audience to ensure that my findings did not fall into the trap of being unique to a single company or product. I also was supported by other students investigating other products in depth, whose results I could leverage to ensure broad applicability of the findings. The case-based approach is also the basis for much of the research in the second phase of LAI initiated last year (the initial phase was largely survey-based), and for many of the CIPD research projects [CIPD], so its value in this type of research is becoming widely recognized.

The second characteristic of our research is that we investigated the problems through several different "lenses", i.e. we applied specific tools from different disciplines to reveal the issues from the standpoint of different people and organizations. Two main tools were used. The first is called "transaction analysis", which is an approach involving interviews about the process followed in the past that supports what Ulrich [1993] calls "product archaeology." We used a tool called the Design Structure Matrix, described in Section 4.4, to document interactions in design processes. Section 4.4 also introduces an adaptation of this tool that I use to present interactions in an assembly. The second approach began under the topic of feature-based design [DeFazio et al] and evolved to the idea of focusing on connectivity and interactions, not on part geometry. Key Characteristics and chains became our way of investigating the physical product.

2.2.2 Group Focused on Mechanical Assembly Modeling

A sub-group that included myself and two other students under Dr. Dan Whitney's supervision all completed work in the field of mechanical assembly modeling in early 1998. My fellow students in this group were Krish Mantripragada and Jeff Adams. Our work is knit in the notion that much about an assembly's interconnectivity, and therefore the integration required, can be studied before any detailed geometric definition begins.

Figure 2-1 describes the relationships between the three bodies of work. My work is conceived for use in concept design to support concept and decomposition selection with an awareness of the integration problems and risk revealed in chains. The output of concept design is a selected concept, which includes a layout and arrangement of the major systems, a decomposition of the selected concept, and the identification of what we call "Assembly Key Characteristics" (AKCs). AKCs are the attributes in each element of the product that contribute to the integral

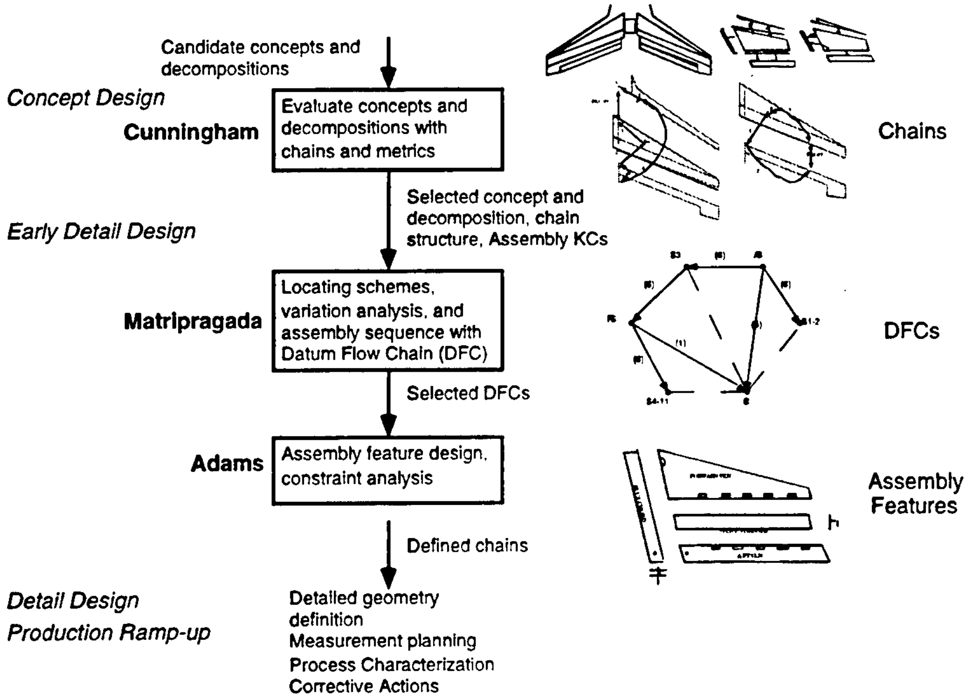


Figure 2-1. Links of three bodies of research in the F&F sub-group studying assembly models.

characteristics of the product, including those that are coupled and conflict.[1] The AKCs are identified in the course of the chain analysis that reveals the product architecture, including the integral characteristics and conflicts. My portion of the overall process "hands off" the AKCs and chain structure of the integral and coupled characteristics for formal analysis in the subsequent steps.

Mantripragada developed a formal chain model called a Datum Flow Chain (DFC) that develops the technical content. Recall that the graphical chain is presented and populated with qualitative information suited to the architecture trade-offs that accompany the decomposition decision prior to the availability of firm quantitative information. The DFC develops the quantitative information that supports the next steps in assembly design: further decomposition to the level of individual parts, assembly sequence selection, design of locating schemes, design of measurement plans, etc. [Mantripragada]. The DFC and the graphical chain carry the same technical basis.

Adams developed a formal approach to selecting the specific assembly features, i.e. the features used in assembly to orient the parts relative to each other [Adams]. Mantripragada's portion of the process "hands off" the selected DFCs and assembly sequence to the assembly feature designer, so the DFC logic is maintained in any selected set of assembly features.

[1] The terms "coupled" and "conflict" are described in Chapter 4. Simply, they are attributes that are affected by the same elements, and therefore they may not be able to be achieved independently.

2.3 Research Description and Methods

My research followed the model described for the F&F program as a whole. The following describes my project specifically in the context of the broader program.

2.3.1 Hypothesis

My hypothesis evolves from the F&F program's missing information hypothesis. As discussed in the introduction, my focus is on integral characteristics or "shared function delivery" among many elements of the product. The interactions that affect function must be understood to reveal the integration risk. Very early in our project I recognized that chains are capable of communicating the missing information and relating it to the delivery of KCs as carriers of product function.

I started with a simple hypothesis that stated that chains could be captured in concept design and used to reveal the integral aspects of the product architecture. As I studied the decisions that create the product architecture, I recognized that a higher level statement was required regarding how identification of integration issues must be emphasized, and how chains in fact become a tool to serve that goal. This statement is captured as the main hypothesis below. There are two main themes of the research: one involves the mechanics of a chain capture procedure to reveal integrality and integration risk, and the second involves the overall method built around chains that leads a multi-disciplinary design team to assessment of integration issues and risk in concept design. Each of these themes is decomposed further into separate points that the research supports. The following is the matured hypothesis statement:

Main hypothesis: A design team's ability to identify the integration issues of candidate concepts will improve with explicit coordination of the many diverse decisions that affect the physical decomposition and hence the product architecture

1. **Chains allow the relative integrality of a candidate concept and decomposition to be estimated by revealing the information needed about architecture: which elements and interactions share in the delivery of particular functions, which companies deliver the elements, etc.**
   a) **chains mesh with existing design theory but also provide a map from decomposition decisions made in the physical domain to their effects in the functional domain that is currently missing in the theory.**
   b) **a procedure for capturing chains can be developed that is applicable to concept design with two properties**
      - **it maintains the scientific basis of tolerance chains**
      - **it includes meaningful metrics that can be applied to the chains for each concept and decomposition to reveal integral characteristics and risks in sufficient detail to aid in evaluating concepts**
2. **A method can be developed that explains how to use chains in a multi-disciplinary design team to evaluate the architecture and integration risk of candidate concepts and decompositions**
   a) **Chains provide a central coordination framework for the team to understand the impact of decomposition options on the architecture, and particularly the level of integration risk that accompanies each option**
   b) **chains can be populated with design, process, organizational, and strategic information; the single representation is applicable in all these views of the product to support early design, process, and strategy trade-offs.**

It is not possible to prove the hypothesis for all cases of product development because every organization and product is unique in some ways. The examples and case studies will only

support or disprove the hypothesis in the cases studied, and extensions will have to considered carefully. It is therefore valuable to carry a counter hypothesis to test as well. If the research proves the hypothesis in the cases studied, then it disproves the counter hypothesis. Therefore, the following is carried as a counter hypothesis:

Counter hypothesis: a design team's ability to identify the integration issues of candidate concepts will *not* improve with explicit coordination of the many diverse decisions that affect the physical decomposition and hence the product architecture.

2.3.2 Summary of Related Work Investigated in the Literature Review

The multi-disciplinary aspect of product development research, and the chain approach as a proposed solution, required a broad literature review. Chapter 3 provides analysis and an in-depth description of this review. The following topics were investigated:

- Three fields of closely related research that describe the processes surrounding functional-physical mapping in product development:
  - design theory, including Enhanced Quality Function Deployment, Axiomatic Design, the method of Pahl and Beitz
  - systems engineering and the underlying basis for decomposition of large systems
  - product architecture, which combines concepts of the other two and presents a language for a multi-disciplinary discussion of the topic
- The management literature addressing strategic issues associated with product architecture, which explains non-technical influences on architecture choices
- The engineering literature discussing the physical and mathematical bases for modeling nominal part-to-part location and tolerance chains that form the basis for the chain procedure
- The broader topic of Design for Manufacturing and Assembly, specifically to investigate whether existing tools are applicable during concept design.

2.3.3 Case Study Method: Deep Case-based Research of Highly Integral Products

Each student on the project was responsible for selecting their case studies and examples. My approach was to begin with assemblies in production to understand the downstream consequences of missing integration information. In 1994 and early 1995, I conducted studies on an aircraft engine nacelle and an automotive body assembly example, each in the context of their corrective action processes. This work was the topic of my master's thesis, also completed on this project [Cunningham]. What I learned was that corrective action processes in automotive and aircraft assembly were similar. However, automotive body assembly was equipped with much more complete assembly intent information than similar aircraft processes. The auto process as a direct consequence operated more smoothly and reached conclusions more quickly. I also learned that it took the auto company and its suppliers about a year to generate, coordinate, and document this information. This level of effort shows that the auto companies recognize the significant value associated with such information.

For my doctoral research, I began to study assemblies that were at an earlier point in the development process. Several students on our team worked together on such an assembly in mid 1995, the horizontal stabilizer of the 767 Horizontal Stabilizer. This assembly was also in

production, but was undergoing a process redesign that allowed us to perform initial testing of our emerging tools. Chains in a much less structured form were part of this study, discussed by Cunningham et al [1996]. This example is described in Section 5.4.

In late 1995, I set out to identify a product to study that was in an early development phase, where the hypothesis could be tested in the true context. It is not easy to form a relationship between a researcher and a company because products in the conceptual phase are highly competitive and sensitive to the company; often only a few people in the company are fully aware of the details. My status as an active military officer also could have been a barrier to forming the required relationship with a defense aerospace company. However, Lockheed Martin Tactical Aircraft Systems (LMTAS) allowed me to study their most important development activity - the Joint Strike Fighter (JSF) - in the midst of the competitive phase. This product satisfied all my needs for a case study: a highly integral product subject to complex architectural trade-offs in concept design.

While I focused almost entirely on the JSF case study for the remaining two years of this project, it was important to avoid a bias toward this particular product and company to validate the research more broadly. This was accomplished in two ways. First, the chain procedure was tested on a few additional examples, which also have an integral character. Also, I tested my conclusions as they occurred by presenting the work to a wide Government, industry, and academic audience. I interviewed and exposed my ideas for critique extensively to others involved in product development in academia and industry through presentations (e.g. three presentations at large LAI meetings and one to a large group evaluating the CIPD research) and personal communications. In addition, I obtained access to government representatives involved in procurement who held many different levels of authority in highly complex product development programs. This approach successfully allowed me to avoid bias to maintain a control in the research. Finally, I was able to follow progress by other students on other examples, and use my awareness of the problems they were investigating to test my assumptions informally.

The end result was a research program that involved a deep investigation of a few product development problems with a broad exposure to others, with a concentration in the aircraft industry and a broad exposure to other products. Appendix A lists my on-site research, presentations, publications, and interviews.

2.3.4 Evaluation Methods

This research method created three distinct forms of evaluation of the hypothesis. The first is my evaluation of the results, which involves a point by point review of the hypothesis in terms of what is demonstrated in the examples and case studies presented in the thesis, with discussion of other products to which I have been exposed. The second involves comments from a questionnaire filled out by several LMTAS personnel and from the intense interaction I have had with the JSF team and other LMTAS employees. This was not a formal survey, but was a means to obtain honest feedback and analysis from members of the company familiar with my work. The questionnaire provides a snapshot of the opinions of a few participants in the study

at a particular point in time, so the results must be assessed based on those attributes of the information alone. These two results are also related in a step by step fashion to the hypothesis. The third is an informal review of the comments I received from presenting my work to a broader audience in the interviews and presentations conducted outside the JSF case study. These comments, serving as an informal evaluation, support my contention of the broad applicability of the chain metrics method.

2.4 Chapter Summary: Guide to Following the Research Method within the Chapters

The research presented in this thesis follows the order in which it was described here. I begin in Chapter 3 with a thorough review of the related work in the literature. This review is somewhat unconventional in that I do not just step through what proved to be an enormous body of work in many fields. Instead, I begin the review by explaining some conflicts within the theory, and between the theory and issues observed in real product development practice. I then step through the literature review and describe the applicable works.

Chapters 4 and 5 develop and illustrate the chain capture procedure and metrics used to evaluate chains as an indicator of integration problems and risk. Chapter 4 explains the principles and rules, the presentation tools, and each metric in the context of the overall framework for chain analysis. Chapter 5 describes four examples. The first three are relatively simple cases where one or a few product attributes are studied to show the broad applicability of the approach and how architecture trade-offs are inseparable from the technical issues. The fourth is a mini case study of the 767 Horizontal Stabilizer that discusses the decomposition trade-offs and how they affect many product attributes.

Chapters 6 and 7 develop and illustrate the full chain metrics method, the framework for architecture analysis of candidate concepts and decompositions based on the chain procedure and metrics. Chapter 6 describes the role that each member of the team from the different disciplines is likely to play. Chapter 7 illustrates the method with the JSF case study.

Chapter 8 presents conclusions and recommendations. It includes a brief review of the main contributions of the thesis, an evaluation of the thesis based on three methods listed above, and a discussion of implementation issues and suggestions for future work.

3. Literature and Related Research Review

This research intends to improve three areas of team performance during concept design: the team's understanding and recognition of the product architecture, the team's ability to document the integral characteristics and estimate the integration risks, and the team's ability to judge whether a product concept is adequate for further pursuit. This chapter reviews and analyzes previous research for its contribution to our understanding of these necessary elements of successful product development. Section 3.1 introduces the point of view from which this review is conducted: a focus on integrality in design. Included are the main definitions of product architecture, the reasons for focusing on integrality, the types of decisions that have distinct impact on product architecture, and the contribution of this research. Section 3.2 summarizes the conflict between design theory and practical issues that arise in the design of products exhibiting some degree of integrality. Because every academic theoretical model of design, be it from design theory or systems engineering, includes a depiction of how the functional to physical mapping is conducted, it is reasonable to critique the existing literature for its ability to address integration issues and to provide tools and guidelines for dealing with these issues. Section 3.3 describes several concepts from the literature, including descriptions of concept design phase milestones and teaming approaches, models of design processes that occur in this phase, and the broader technical and strategy issues of product architecture that heavily influence this phase. Also described are the assembly models which provide the underlying basis that is applied in the chains approach. Section 3.4 introduces a framework for architecture definition that builds on existing theory but better reflects issues faced in design of integral products, and summarizes two research themes that are pursued in the remaining chapters.

3.1 Applying a Focus on Integrality to the Literature Review

This review is conducted from the viewpoint of a focus on integrality. To understand what that perspective entails, three interrelated topics are introduced here: product architecture, classification of integration risk, and the impact of decomposition on the architecture. This section concludes with an introduction to contribution of this research, the reason for focusing on decomposition, and the rationale for exploring the use of assembly modeling to solve the problem.

3.1.1 Basic Definitions: Modular and Integral Architectures

Product architecture is the name now given to the scheme by which functions are assigned to physical elements and the interactions between those elements are defined [Ulrich, Ulrich and

Eppinger]. Product architecture is defined in two categories:

- *Modular*: a strong one-to-one mapping of functional elements to physical elements (depicted in Figure 3-1a by the functional hierarchy with a matching physical hierarchy) where the role that interfaces among the physical elements play in delivering function is well understood. Modular products are attractive because, by functionally decoupling the physical components, the components can then be designed and made somewhat independently. As a result, the design process and downstream integration of the product are made less complex. Modular products better accommodate producibility and strategic objectives such as upgrade, additions, adaptation, product variety, and process flexibility, through many different types of modularity [Ulrich]. However, modular products are often "clunky", i.e. awkward, and do not optimize performance on global measures like space, weight, etc. [Whitney 1996].
- *Integral*: a complex mapping of function to many physical elements, where the effect that the inter-element interfaces have on function is complex [Ulrich]. Ulrich and Eppinger say that the interactions among elements may be "incidental" in that their effects on function may be difficult to recognize. Functions are distributed among many elements, as shown by the lines that run laterally among the physical elements in Figure 3-1b; these "integral characteristics" would not be present in a fully modular design. Integral architectures generally exhibit better performance in global measures at the expense of the "strategic" (i.e. upgrade, additions, etc.) attributes listed above for modular products [Whitney 1996, Ulrich and Seering, Ulrich]. I use the term "inherently integral" to refer to products that have many functions shared by many of the same physical elements. Functions in inherently integral products are delivered in a *coupled* fashion, i.e. a change in one product feature, part, or sub-element can affect system performance in many functions.

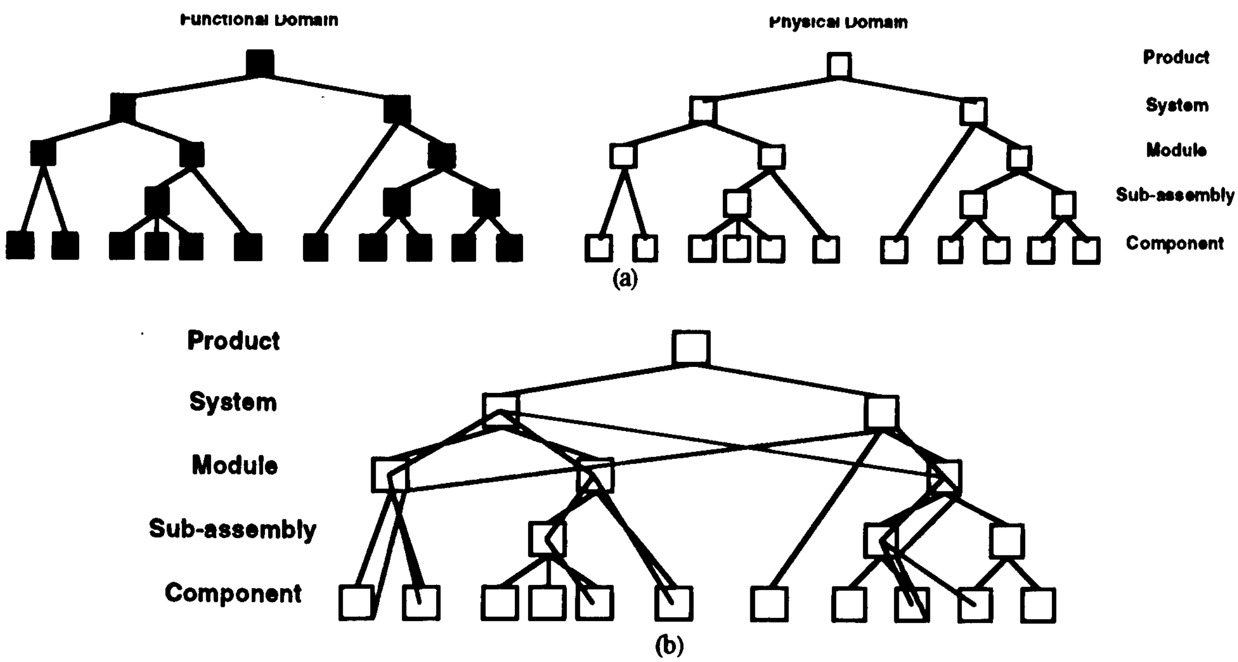


Figure 3-1. (a) A modular architecture has (among other attributes) a close match between the functional and physical hierarchies, while (b) an integral architecture has functions that are dispersed among many physical elements in complex patterns.

The design theory literature often represents modular as a kind of ideal. When it is not reached, according to the theory, the reason is that the designers could not achieve it, or else they did not do as good a job as they should: their design is inferior. In reality, designs with integral character can be superior and represent a high degree of success by the designers in achieving their goals [Whitney 1996, Ulrich and Seering, Ulrich]. The fact is that designers must try to achieve many goals. More often than not those goals conflict with each other and cannot all be attained equally well. Rather than criticizing the designers for failing to achieve a modular design, we should recognize their achievement of a reasonable number of conflicting goals to a reasonable degree. Even many simple products exhibit some degree of integrality [Ulrich and Ellison], and complex "inherently integral" products do not conform to the ideal models because modularity cannot be achieved or may not be desirable. This is true even if only engineering issues are included. The situation is further complicated when strategic issues like outsourcing and new architecture development (to name a few) are added. Therefore, from the viewpoint of research in product development, it is important to maintain an openness to the relevance and usefulness of both modular and integral architectures.

3.1.2 Integration Risk

Though integral designs may be in fact superior in some situations, it is clear from the literature and experience that integral designs do demand special attention during product development. They pose unique risks that must be managed actively so that no surprises are encountered far downstream. All designs entail some risk, so it is useful to classify two distinct categories. *Module risk* is the possibility that any one element will not fulfill its part in the design; it will not perform, can't be made for the expected cost, can't be made on time, etc. *Integration risk* is distinctly different. It is the possibility that even adequately designed or built modules will not perform together because their interaction also affects how they function as a whole. Furthermore, integration risk is worse than module risk because 1) it is usually encountered late in the product development process and 2) diagnosing it is difficult. Integration risk therefore readily spawns the three major types of risk: cost, performance, and schedule risk.

By definition, if we had a truly modular design, there would be little integration risk associated with function because the role that the interactions among elements have on function is well understood and therefore integration tasks can be planned up front. Therefore only integral designs face the possibility of integration risk associated with function. A team can not just expect it will all work itself out. The team must identify the risks and mitigate them actively. Even then problems with integral characteristics persist because:

- every product has an architecture, and that architecture will be created in concept design, consciously or not
- architecture decisions may result in integrality, sometimes unintentionally, which spawns integration risk
- architecture decisions are made in concept design, and therefore are susceptible to error due to weak or fragmented information; predicting such far reaching effects like integration (which may be years away) is no simple task.

3.1.3 How Architecture is Created

The ability to identify the architecture, and particularly the integral characteristics, during concept design would be a distinct source of advantage for a manufacturing firm by allowing it to avoid or at least mitigate integration risk. The product architecture is so important to all technical and strategic issues of product development that it must be consciously designed. Yet in many real products, we find unexpected integrality in the architecture that must be overcome well downstream in design or production. In my experience these surprises can be traced to a failure to identify and evaluate the architecture accurately at the time it was set - in concept design.

What are the key decisions that create the architecture? The goal is to understand why it is that architecture remains such a slippery characteristic for design teams to identify even though models from design theory attempt to show how it is created. These design theory models are described in detail in Section 3.3.2. All design theory models contain two main parts that have direct relevance to how product architecture is created:

- mapping: the translation of customer needs into technical specifications (or functions), which are in turn translated into physical attributes, and then into process attributes.
- decomposition: the act of breaking a large problem (a function that must be performed or a physical entity that must be designed) into a set of smaller problems or smaller elements.

As described in more depth in Section 3.2, the models from design theory do not fully capture integrality because they do not prescribe ways that decomposition *really happens* in design of products that exhibit some degree of integrality. The models prescribe mapping and decomposition each in one way only. In fact, when we recognize how decomposition really occurs, we see that the two decisions are inseparable because decomposition decisions influence the mapping. Integrality may be created unintentionally, and this integrality would not be identified if the design theory model is followed.

3.1.4 Contributions of This Research

I approach this problem by accepting the fact that some products may in fact be inherently integral, or that an integral design's good may outweigh the bad so that integrality may represent good design. When this is the case, two distinctions are important: what product functions are delivered in an integral character, and what level of integration risk accompanies this integrality. If an integral solution can be found that poses relatively low integration risk, the design will have the potential to be superior to a modular design while injecting little additional risk. Because architecture is set by the end of concept design, we are forced to analyze this complex problem in an environment where little detail definition is available. Finally, because architecture touches all major technical and non-technical decisions, which often conflict, we must analyze the problem in the context of these many diverse decisions. Figure 3-2 summarizes the above discussion by placing existing research and this thesis in a framework of architecture choices.[1] Each case is developed in the discussion of Section 3.3. This thesis makes its contribution by focusing on the two boxes on the right hand side, where integrality is part of the solution. I develop a method for architecture analysis that stems from decomposition choices and support it with a set of tools.

[1] This matrix is described in Section 1.2

Functional Requirements		Physical Elements: One or a few	Physical Elements: Many
	One delivered by:	**Modular Characteristic**	**Integral Characteristic (chain)**
	Many delivered and shared by the same:	**Function Sharing**	**Coupled Integral Characteristics (coupled chains)**

Figure 3-2. A matrix of architecture choices emphasizing the contribution of this research to products that exhibit integrality.

There is a fundamental difference in my perspective of how architecture is created, as compared to existing design theory, that requires a focus on the choice of decomposition. The design theory and systems engineering approaches state that interactions among physical elements that impact function are dictated as part of the mapping process. Therefore this insight into the interactions can be utilized to select the best decomposition. And, since a modular solution is prescribed, these interactions should be minimal and well understood. In my viewpoint, *decomposition creates new interactions, that in turn must be recognized systematically and used as criteria to judge the appropriateness of the decomposition.* These new interactions are part of the functional-physical mapping. My work here in fact tries to achieve the same goals as the design theory - find a relatively modular design, or at least minimize integration risk - but my approach attempts to open the theory to other decisions that impact the architecture. Specifically, I focus on those decisions that cause decomposition to occur in the physical domain, which create unforeseen interactions in the function-physical mapping that are not currently reflected in design theory.

Given that this thesis will aggressively look at the integrality born out of physical decomposition decisions, we require a set of tools that can be used to recognize the integration issues that arise in different decompositions. It is not clear at this point what unified basis can be used to develop tools applicable in any domain. In my work I chose to focus on mechanical assemblies, where an established modeling and mathematical basis exists that could support this need. This choice of focus limits us to domains where functions are delivered by physical dimensions in the product.[2] Two observations motivate the use of assembly models to expand the prescriptive models to better reflect the impact of decomposition decisions in a product's integrality:

- experience shows that when assembly is injected into the design process, integration issues surface, and
- a specific type of assembly model called *chains* readily shows contributions to function delivery shared in many elements and their interactions, and also indicates coupling.

According to Whitney: "Assembly can be the glue in concurrent engineering." This statement is based on experience in real industry design problems where integration issues were brought to the fore when assembly was injected into the discussion. Why does assembly have this effect?

[2] This does not constrain us solely to mechanical products. Many electrical and optical products, for example, exhibit integral functions that are delivered by physical dimensions.

Recall the experience I shared in the introduction, that assembly is more than just putting parts together and fastening them. Assembly is the place where integration occurs and the product comes to life. Architecture issues appear explicitly in the assembly of complex electro-mechanical products, where delivery of top level requirements is shared in complex ways across parts, sub-assemblies, processes, and even multiple companies. Assembly is the integration point of all these technical and non-technical factors. Therefore, assembly models that can be applied in concept design are well suited to act as an indicator of integral character in the product.

3.2 The Conflict Between Theory and Practice

This section explains the conflict found between theoretical models and practical approaches to the two main decisions that create architecture: functional-physical mapping and decomposition. The design theory models "prescribe" how these two decisions occur in a way that in practice, when related to development of integral products, is difficult to implement, or if followed may not enable the cross-functional design team to identify the integration issues and risks. The following is a summary discussion of this issue. It is based in the design theory described in greater detail in Section 3.3.2. The practical observations are based in my own case studies and findings from many other researchers. Two examples from the Joint Strike Fighter (JSF) case study are introduced here to illustrate the conflict.

Three large bodies of literature - design models, systems engineering, and product architecture - prescribe how to make the mapping and decomposition decisions that impact architecture. The three bodies share two major similarities: functional-physical mapping is recommended to be executed by the *assignment* of functions to physical elements (implying a single decision direction)[3], and decomposition is uniformly depicted as occurring in the functional domain alone (never in the physical domain). Design models and systems engineering share a third characteristic: *modularity* is the recommended architecture.[4]

3.2.1 Functional-Physical Mapping and Decomposition in Design Models

I use the term "mapping" to refer to the translation of customer needs into technical specifications (or functions), which are in turn translated into physical design characteristics or attributes, and then into process attributes that create production requirements. Mapping is represented in Figure 3-3 by traditional Quality Function Deployment (QFD) [Hauser and Clausing]. I use the term "decomposition" to refer to the act of breaking a large problem (a function that must be performed or a physical entity that must be designed) into a set of smaller problems or smaller elements. Figure 3-4 shows a functional decomposition that is mapped to a matching physical decomposition[5], corresponding to a fully modular design.

The process shown in Figure 3-4 - called "zig-zag" [Suh] - is prescribed by design theory:

[3] Some systems engineering and product architecture literature presents an openness to discovering aspects of the mapping that are derived from or incidental to the physical solution, as described in Section 3.3.2.
[4] Specifically, the systems engineering literature states that a decomposition should be selected that minimizes the interactions among the physical elements; see Section 3.3.2.
[5] The way to interpret these trees is that all elements that are the children of an element are sub-sets of the content of the higher level element.

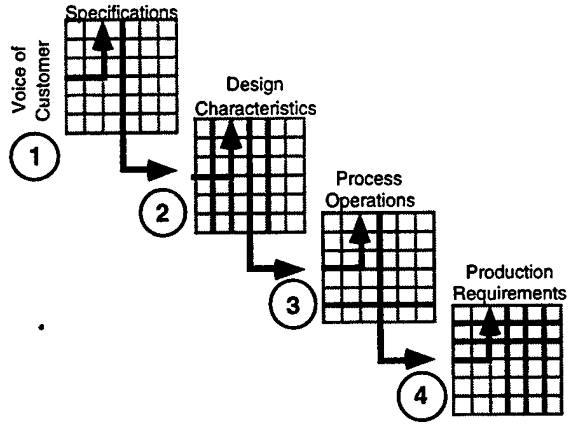


Figure 3-3. In QFD, downstream decisions are traceable back to customer needs through the four matrices. Functional to physical mapping occurs in matrix 2.

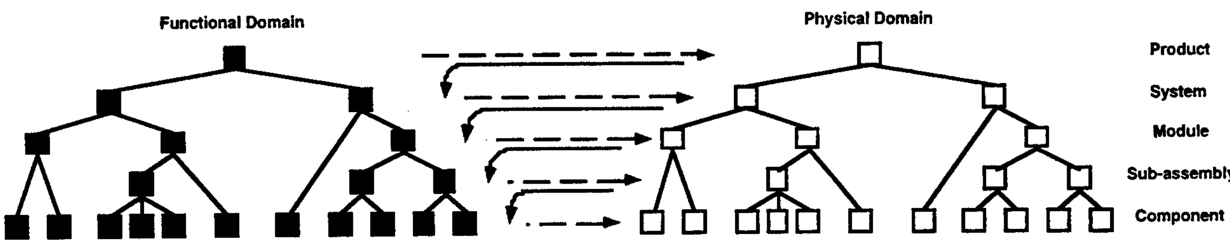


Figure 3-4. A functional and physical hierarchy for a modular product (one-to-one mapping) as prescribed in design theory: functions are assigned to physical elements and decomposition occurs in the functional domain.

- mapping at any level occurs as the functions are *assigned* to distinct physical elements (shown by the dashed arrows from left to right), so the architecture is *dictated*, and
- then the physical solution is used to guide decomposition in the functional domain (shown by the solid arrows that move back to the functional domain horizontally and vertically *only in the functional domain*).

3.2.2 The Conflict: Physical Domain Decomposition Alters the Mapping

There is a conflict between the design theory model and real product development:

> **In real product development, physical domain decompositions are prevalent, and they alter the functional-physical mapping.**

In real product development, several members of an Integrated Product Team (IPT), a cross-functional design team involving design/performance, producibility, and technology and outsourcing strategy, influence the decomposition to attempt to meet each constituency's objective. When a decision involves how the product will be decomposed into physical elements suited to the objectives for how the product will be fabricated, assembled, supported in the field, outsourced to partners and suppliers, or delivered by new or existing technologies, it is made in the *physical* domain. Any such decision involves decomposing the physical article, not the functional article.[6]

[6] Many examples of these types of decisions are discussed in Chapter 5.

When a design is modular, there is direct homology between the functional and physical domains. Decisions can be made in either domain without altering the mapping, which is nearly one to one. So, in modular cases, physical domain decomposition does not appear to complicate the process posed in design theory.

Functional decomposition is an incomplete portrayal when an *integral* design is impacted by decisions made in the physical domain that influence decomposition choices. I have observed two main scenarios. In one, the design/performance group on the IPT is comfortable with and equipped for a limited amount of functional decomposition. Instead of decomposing functions and mapping them to the associated physical elements, designers map many functions to one high level element of the product. From this point on in the design process, decomposition takes place in the physical domain and the resulting architecture styles (modular and integral) at levels further down in the hierarchy are not easily predicted (depicted notionally in Figure 3-5). The sub-elements selected in the physical domain do not necessarily correspond to sub-elements in the functional domain, so functions may end up being delivered in many elements and their interactions. In the second scenario, the design/performance group may continue to decompose the functional article. But, producibility and strategic objectives carry equal or greater influence, and these objectives weigh in on the physical side because functions are irrelevant to these choices without a corresponding physical element. This latter case occurs when there are contending pressures among performance, producibility, and strategic objectives.

My work shows that physical decomposition alters the functional-physical mapping in surprising ways, creating new interactions that alter function. Instead of architecture being actively shaped by functional groupings, architecture becomes a *fallout* of these decisions that involve physical domain decomposition. The way the functional hierarchy maps to the physical domain may be more complex than the designers intended, creating the incidental interfaces between physical elements whose effects on function are so difficult to predict. This finding addresses two observations made by Finger and Dixon [1989] regarding functional-physical mapping and the degree of modularity:

- "the mapping between the requirements of a design and the attributes of the artifact is not understood"
- concept design aims to decompose the problem into independent sub-problems (i.e. decompose the product into a modular architecture involving many smaller pieces to be designed and produced separately), but "complete independence is seldom, if ever, possible."

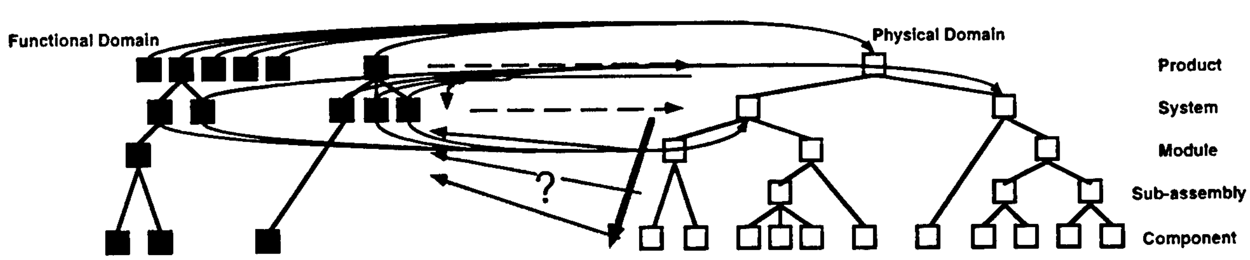


Figure 3-5. Functional allocation at the system level followed by intermittent patterns of functional and physical decomposition, with an unknown mapping as the result.

Figure 3-6 summarizes the three interrelated issues of decomposition, functional-physical mapping, and architecture style, in the context of the conflict between design theory and practice. First, there are valid technical and non-technical reasons for physical domain decomposition. However, when physical domain decomposition involves elements that embody integral characteristics, the resulting functional-physical mapping is unclear. Were all products modular, this would not pose a concern. However, modularity in fact is not an ideal in all cases because designs must satisfy many requirements, often conflicting, that may lead designers to choose an integral design.

3.2.3 The Impact of the Conflict

The risk of an inaccurate or incomplete mapping is clear: integrality is inaccurately documented. Interactions among physical elements that affect functions, like in Figure 3-1b, can become orphans during the early phases of the development process and create integration risk. Integration requires an explicit awareness of all the elements that must be coordinated to ensure that the product will function as a whole. If the mapping is wrong, there are potential

Decomposition

Functional:
- to satisfy technical criteria
- suitable when a function can be broken down into sub-sets

Physical:
- to satisfy technical and non-technical criteria
- alters the functional-physical mapping
- creates interactions among elements whose role in the delivery of function is difficult to identify

(a)

Functional-physical Mapping

When architecture is modular
- direct functional to physical homology
- decisions in either domain are traceable to the other

When architecture is integral:
- no direct functional to physical homology
- mapping altered if physical decompositon occurs, underestimates integrality

(b)

Architecture

Modular:
- minimizes complexity, enables many strategies to be implemented
- often clunky, i.e. global technical parameters suffer

Integral:
- optimizes global performance parameters
- integral characteristics may pose integration risk
- forces trade-offs between performance and implementation of strategy

(c)

Figure 3-6. Relationships between (a) decomposition, (b) functional-physical mapping, and (c) architecture style.

contributors to functions, or coupling of function delivery, that will go unrecognized. If the integration issues are not found until the integration phase - assembly - a great deal of redesign may be required, rework will creep into production, and ultimately cost, performance, schedule, and quality will suffer.

To further emphasize how common this conflict is, the results of a recent survey involving 225 products are illuminating. The survey covers a large range from simple consumer to complex defense products. Ulrich and Ellison [1997] found that the delivery of the few key features that differentiate the products surveyed from their competitors were very often "holistic" (integral) in nature in that they are shared among many elements of the product in complex ways. This observation makes two key points. First, integral characteristics are quite common, not isolated to a few complex products like airframes. Second, the most critical attributes that warrant extensive attention in the design process - those that differentiate the product - are often integral.

In addition, the conflict is at the heart of real design issues faced in industry. Currently, a developing design approach in industry is focused on what are called "Key Characteristics" (KCs).[7] KCs are used by industry to focus design teams on the product attributes that most affect customer satisfaction, safety, or compliance with regulatory requirements [Lee et al]. This in practice achieves what Clausing calls "focus on the critical few." Companies recognize that some characteristics of the product dominate the attention and effort of the design team. The KC approach attempts to focus the IPT on physical attributes that are the carriers of requirements that are key to the customer. Again the Ulrich and Ellison finding is important in that the "critical few" are often integral, so KCs are expected to be integral. So while design teams may not even think they are using design theory, in fact with the KC approach they are attempting to understand their mapping and use it throughout the development process.

Current KC practice is characterized by inconsistent methods of identifying, tracking, and communicating about KCs, though the movement is widely accepted [KC]. The KC approach is intended to integrate quality into design and production, but is not uniformly applied based on sound principles. Two steps are prevalent in more structured processes. First, QFD-based approaches are prominent, structured, and successful in relating function to high-level product attributes that are labeled "KCs." So the method would appear to relate functions to physical attributes. However, these physical attributes are often integral, or are high-level product attributes that can not be related to specific parts, processes, and suppliers.

Because the KCs are often integral, a second step called "flowdown" is required. Flowdown is the term used to refer to the identification of attributes in all physical elements that combine to affect the end attribute. Flowdown occurs in the physical domain. In practice, attempts to systematically flow down KCs to attributes of individual parts, features between parts, or features of processes, are typically judgment based. A judgment based mapping method is likely to be inconsistent or result in incorrect flowdown, and subject to the same conflict seen between the mapping approach described in theory and practice related to real products exhibiting some degree of integrality.

[7] Some call these critical or significant characteristics.

3.2.4 Illustration of the Mapping and Decomposition, and the Conflict Between Theory and Practice

The following two JSF example functions illustrate the conflict. I begin by showing how mapping and decomposition is prescribed to proceed in theory. I then explain why these solutions are unacceptable, and are altered by other decisions in the physical domain.

3.2.4.1 Two JSF Examples of Mapping and Decomposition Following the Theory

One airframe function is "sustain the loads experienced in flight", which is shown at the top of a functional hierarchy in Figure 3-7. A physical solution is a frame that forms a structure. Back in the functional domain, we decompose the function into "sustain longitudinal loads"[8], "sustain lateral loads"[9], and "sustain other loads." A physical solution for the longitudinal loads is a long "keel beam" (an I or box beam, perhaps) that runs the length of the airframe. Physical solutions would also be selected for the other sub-functions. In theory, no further decomposition of "sustain longitudinal loads" is needed because the sub-function is assigned to a single part. In practice, as described below, we see that additional decomposition *does* occur - in the *physical* domain.

A second requirement is "carry weapons." The physical solution is an internal weapon bay.[10] Back in the functional domain, two sub-functions required for this physical solution are "provide access to environment" and "support weapons."[11] The respective physical solutions are a door/hinge module and a lug frame.[12] Two sub-sub-functions for "provide access to environment" are "provide a translating surface" and "provide motion." The respective physical solutions are a set of doors and a set of actuated hinges. The hierarchy is shown in Figure 3-8a and a sketch of the solution is shown in Figure 3-8b. In theory, these elements that implement each function should represent a sound design, or even an ideal design. In practice, due to global performance requirements, this functional-physical mapping is not a viable candidate.

3.2.4.2 Illustration of the Conflict

The conflict arises when we try to synthesize these two and many other requirements into an airframe that optimizes several competing global requirements: minimum weight, efficient spatial arrangement of systems (like internal weapons), minimum overall shape (or shape that provides best aerodynamic properties), etc. Therefore a physical element like a "lug frame" in the weapon

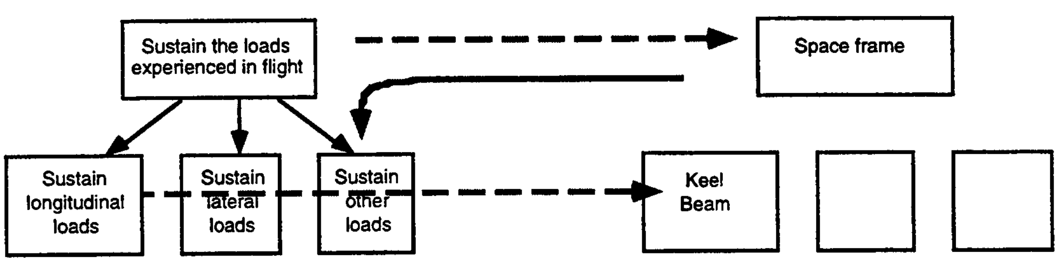


Figure 3-7. Mapping and decomposition associated with the keel beam that follows design theory.

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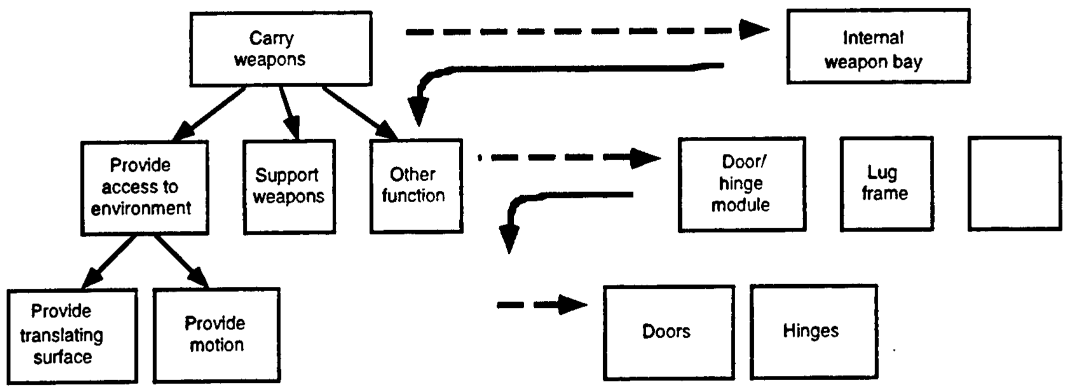
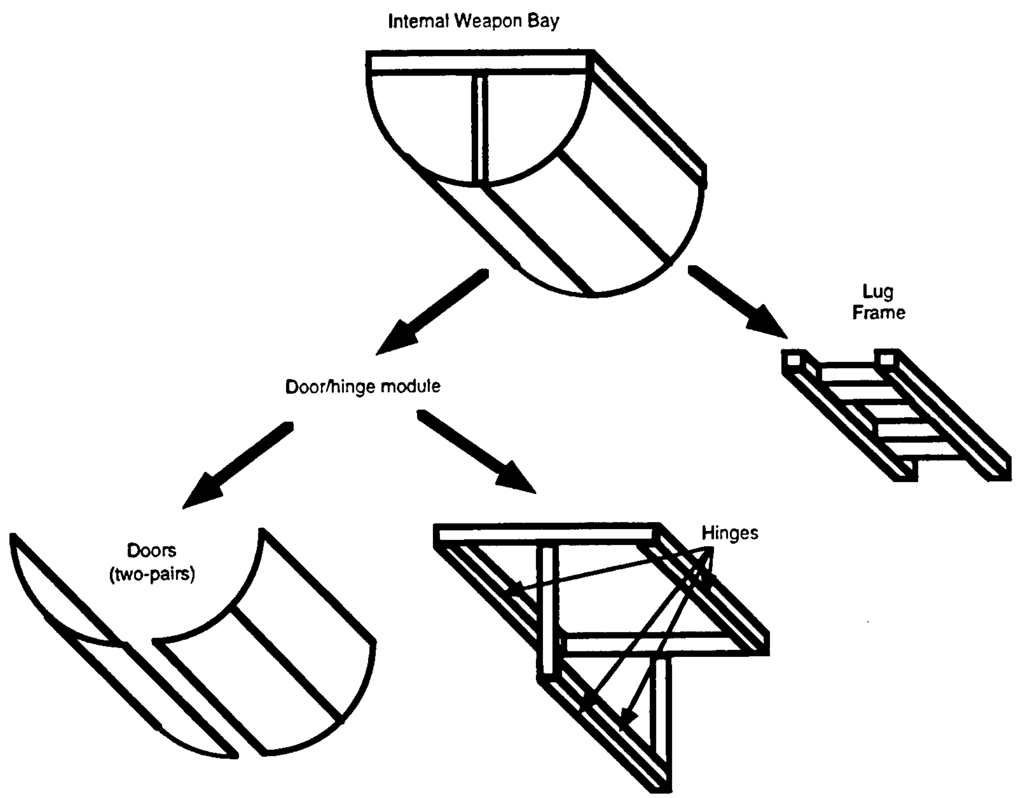
[8] These run from forward to aft in the airframe.
[9] These run from side to side in the airframe.
[10] A volume inside the airframe where weapons are carried.
[11] This is non-trivial, many weapons weigh 1000lb or more.
[12] Weapons hang on "lugs" attached to a structural frame that can support their weight.



(a)



(b)

Figure 3-8. (a) Mapping and decomposition associated with the weapon bay that follows design theory, and (b) a sketch of the solution that matches this approach.

bay could never be an independent element because it is too big and heavy. Because the airframe performs many functions, such a modular approach would lead to many such "ideal" elements that, combined into an airframe, would create a kludge that would be too heavy, poorly arranged, and too big. Instead, the requirement "support weapons" must be achieved in an integrated, lightweight airframe that also carries loads, positions other systems, etc.

3.2.4.2.1 Example: Global Parameters Lead to Many Functions Shared Among the Same Parts

The weapon bay example shows how global performance parameters lead designers to share many functions in the same high level elements, leading to what I call "coupled integral

characteristics." As opposed to the types of elements shown in Figure 3-8, the real weapon bay will be formed by elements that have several other jobs as well. For instance, there will not be an element that houses the hinges like that shown in Figure 3-8b. Instead, the hinges will be supported at the two ends (and in other places along the length) by structural elements that do other jobs in and outside the weapon bay. The design group is equipped to proceed with a high level configuration tradeoff involving many functions shared in a single airframe. Figure 3-9 shows a top view of the airframe layout in the JSF case and the points where the hinge lines terminate. There is no distinct physical element that delivers weapon bay function.

In order to assess the level of integration risk, the IPT is required to identify the mapping of hinge function to the physical elements that deliver it. Hinge function is largely delivered by the proper dimensional alignment of the two ends of the hinge line. In the ideal design, the hinge lines are part of a single element. In order to determine the risk of delivering the alignment, and hence the function, in the ideal case, the IPT would need to just evaluate the design and process for the hinge line housing. But we know this solution is not possible.

In the integral design, hinge alignment, and hence function, will not be affected solely by one element. It will be affected by all the elements that play a role in positioning the four hinge lines at their ends, as well as by the hinge itself. What elements will have a say in this function? The answer is not obvious, and a judgment process is unlikely to consistently answer such critical questions. The mapping of hinge line function therefore is unknown and entails unknown integration risk. Such unknowns in design are unacceptable and a recipe for disaster.

3.2.4.2.2 Example: Technical and Non-technical Reasons Why Physical Decomposition Occurs

The keel example shows why physical decomposition occurs, and how it alters the mapping. Recall that the keel, in theory, is a single long beam that runs the length of the aircraft along its centerline. In the integral reality two issues change this element. First, a single keel can not be used because the space in the center of the aircraft must be occupied by other systems. This splits the keel into left and right keels, as shown in Figure 3-10a. This is a technical reason for

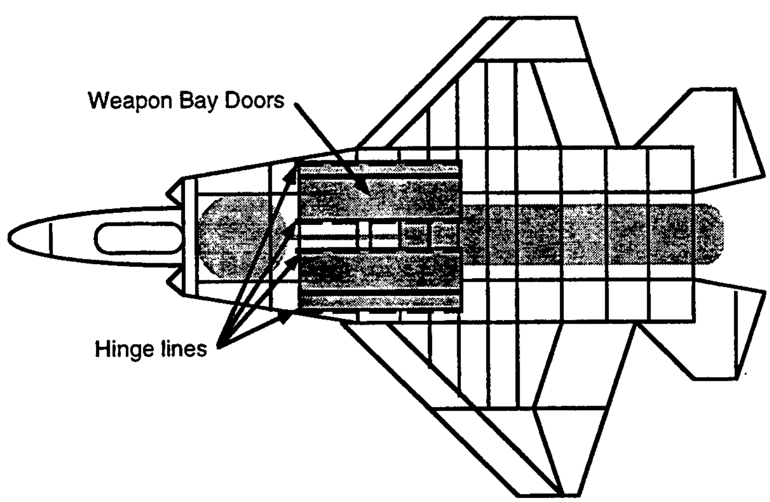


Figure 3-9. Top view of the JSF airframe showing how weapon bay hinge lines will be supported in an integral design.

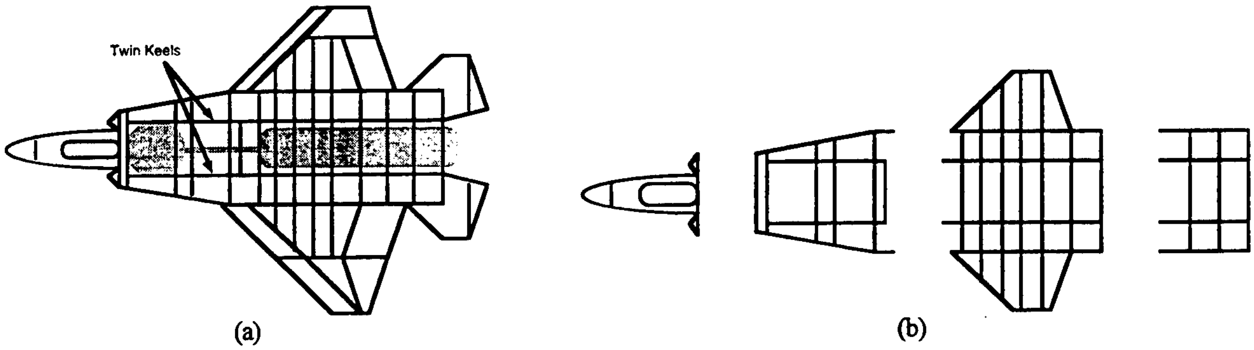


Figure 3-10. How keels are altered by physical domain considerations: (a) one theoretical keel is split into left and right keels due to competing spatial constraints, and (b) the keels then must be further decomposed due to assembly and/or strategic constraints.

physical decomposition of an ideal element. Second, the keel attaches to many other elements of the airframe, also shown Figure 3-10a. From an assembly perspective, this creates a huge problem. If the two keels are not segmented further, the resulting assembly process would be so inefficient that the airplane would never meet its cost target. If every piece had to be connected to the full-length keels, the critical path in assembly would be very long. There may also be concerns regarding whether an appropriate assembly process technology could make such an assembly. Further, the aircraft must be broken into several pieces to satisfy strategic issues like outsourcing or platform goals. So, the keel is likely to be broken into more than two pieces where work can proceed in parallel, for example in the decomposition shown in Figure 3-10b. These are producibility and strategic reasons for physical decomposition.

As a result of these perfectly valid physical decomposition decisions, longitudinal load carriage is split among many elements that contain segments of keels. Greater integrality results from the physical decomposition decision. The requirement for "sustain longitudinal loads" is now affected by how well the keel pieces are aligned. What physical elements affect this alignment, and hence the function? Again, this is an unknown. Without identification of this mapping, the architecture and integration risk are unknown.

3.2.4.2.3 The Potential for Coupling

It also happens that the decomposition in Figure 3-10b splits both the keels and the weapon bay hinge lines. The same elements and interactions now affect each, resulting in coupled integral characteristics. How will this coupling impact delivery of the two functions, and the degree of integration risk? Without a mapping procedure that captures the two, this too remains an unknown. Can this coupling be avoided? Perhaps it can, but what other integration issues and coupling will result if that path is taken? Again, these issues are not indicated by the theory when the designers are forced to take an integral path.

3.2.5 Summary of the Conflict

The theory states that mapping and decomposition, the two decisions that create a product's architecture, are separate. Further, the theory prescribes how mapping and decomposition are to be executed. In practice, two valid issues alter the prescribed model: physical domain decomposition, and the need for integrality. As a result, the functional-physical mapping can not

be fully and accurately documented if the theory is followed. Without the mapping, the architecture and integration risk remain unknowns, which leaves the IPT in an unacceptable situation.

3.3 Product Development and Design Theory and Methodology Research

Recognizing the conflicts discussed above, the challenge is to develop a prescriptive model that can accommodate the issues of integral designs. This section reviews design theory more rigorously. First, I introduce the typical design phases represented in the models. Emphasis is on the "concept design" phase and the industry trend toward Integrated Product Development (IPD)[13], which is cast in the emerging theory called "3D Concurrent Engineering" [Fine]. Next, I explain in more detail the design theory and systems engineering models that depict mapping and decomposition which are based on overarching design principles or axioms that emphasize modularity. These models and the architecture literature are then compared. Finally, the conflict between the theory and practice motivate the exploration of assembly models to advance the design theory models toward representation of products with integral architectures. This section therefore also includes a review of existing assembly modeling tools and analysis methods.

3.3.1 Descriptions of Concept Design

Concept design is the phase where many candidates are generated and one of them is selected that is judged to best satisfy customer and strategic needs, with minimal risk. This phase is critical because the majority of the cost of the product is committed in this phase even though a small percent of the resources are expended (see Figure 3-11) [Nevins and Whitney, referencing numerous industry studies]. Concept design is unique in that the decision space is huge but the information available to make those decisions is incomplete or sketchy at best. By the end the team must make its choice based on whatever information is available, and document the choices and inherent risks into a plan to execute the design and production of the selected concept while overcoming the risks along the way.

3.3.1.1 Relation of Concept Design to the Canonical Design Phases in Product Development

All models of design processes (several are summarized in [Finger and Dixon] and [Tate and

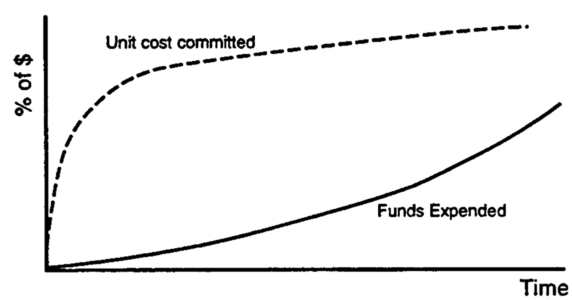


Figure 3-11. Industry studies show half to three quarters of the unit cost is set in concept design and early detail design though these phases expend a small percent of the resources.

[13] IPD, also called concurrent or simultaneous engineering, is a development approach where traditionally sequential tasks are overlapped to improve the process, and functional organizations are teamed to ensure agreement as design evolves.

Nordlund]) describe a few distinct phases of design that begin with "concept design", "concept development", or "concept exploration." Each phase presents a unique decision environment for the design team and has distinct milestones. Figure 3-12 shows the DOD product development phases [DOD-I 5000.2], a set similar in content to those posed in many other writings [e.g. Ulrich and Eppinger, Clausing 1994].

The output of concept design is the selected concept and a target specification for the design that includes performance measures, production requirements, cost estimates, identification of suppliers with the necessary capabilities to deliver the major elements, and the risks to meeting cost, performance, quality, and schedule. The selected concept comes from a comparison of two or more candidate concepts that as a minimum should be based on performance, cost, risk, compatibility with the overall corporate strategy, and any other factors; the concept that best balances these often competing factors becomes the selected product concept.

3.3.1.2 Milestones Within Concept Design

In order to substantively assess the cost, performance, quality, and schedule for different concepts, a "system" design is required that includes[14]:

- a *layout* - identification of systems that implement the main functions, especially key performance issues that result in the identification of Key Characteristics (KCs)[15] and a rough arrangement of critical systems and sizing of the product to study performance,[16]
- a product *decomposition* - candidate sub-elements as they would potentially be fabricated and assembled, permitting a study of manufacturing and cost, and
- a reuse strategy and *platform plan* - identification of which elements are common to other variants of the product line, permitting a study of cost and strategy across the spectrum of company products.

Note that architecture is influenced by each of these elements of the system design. *No one step completely defines the architecture.*

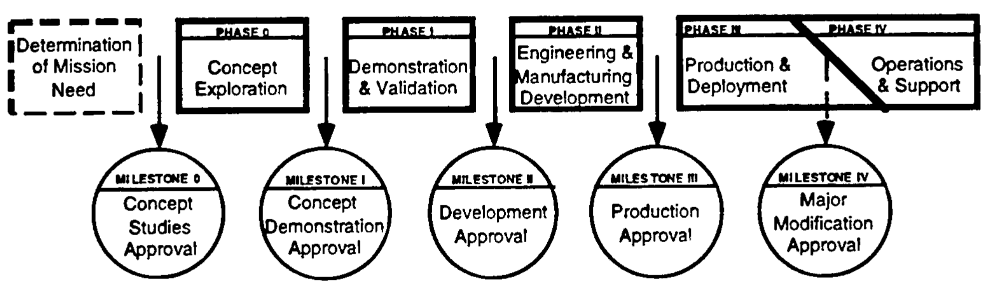


Figure 3-12. Product development phases in the DOD acquisition model.

[14] Ulrich and Eppinger [1995] show system-level design as an activity immediately following concept design (development) and selection. However, the two are so closely knit that it is unlikely that a design team could select a concept without the insight provided by the system design. Hence Whitney [1997] incorporates this separate activity as a central part of concept design to enable a rational concept selection to occur.

[15] A topic discussed in Section 3.2.3.

[16] This may also be called "configuration."

Besides the system design, each concept includes at least the following in order to compare the concepts, as shown in Figure 3-13 [Whitney 1997]:

- an estimate of the candidate processes needed to fabricate and assemble the sub-elements identified thus far in the decomposition,
- a strategy to implement the processes efficiently,
- a technology investment strategy to develop the product and process capabilities,
- a supply chain strategy to identify who will develop the technologies and ultimately design and produce the product, based on the best balance of cost and capability,
- identification of high risk areas.

All of these factors are required to make a sound selection from among the candidates.

In reality, concept selection is a recurring process throughout design from the system level to component and part level [Clausing 1994]. In concept design decomposition will stop at some level because not all components and parts will be identified, only those that can be identified at that stage and that need to be due to their potential impact on concept selection. Decomposition will not be complete, but must be described to sufficient levels to reveal the complexity of the architecture, its suitability to the strategy, and risks.

3.3.1.3 3D Concurrent Engineering (or IPD)

Companies today organize their development teams in varying degrees along the lines of multi-disciplinary groups dedicated to single or a few projects. The value of IPD has been well-documented over the last two decades as many manufacturing firms in the United States have adopted this approach [e.g. Whitney 1988, Nevins and Whitney, Clausing 1991, and Clausing 1994]. The teaming of design and producibility members in an IPT is a given in any competitive firm.

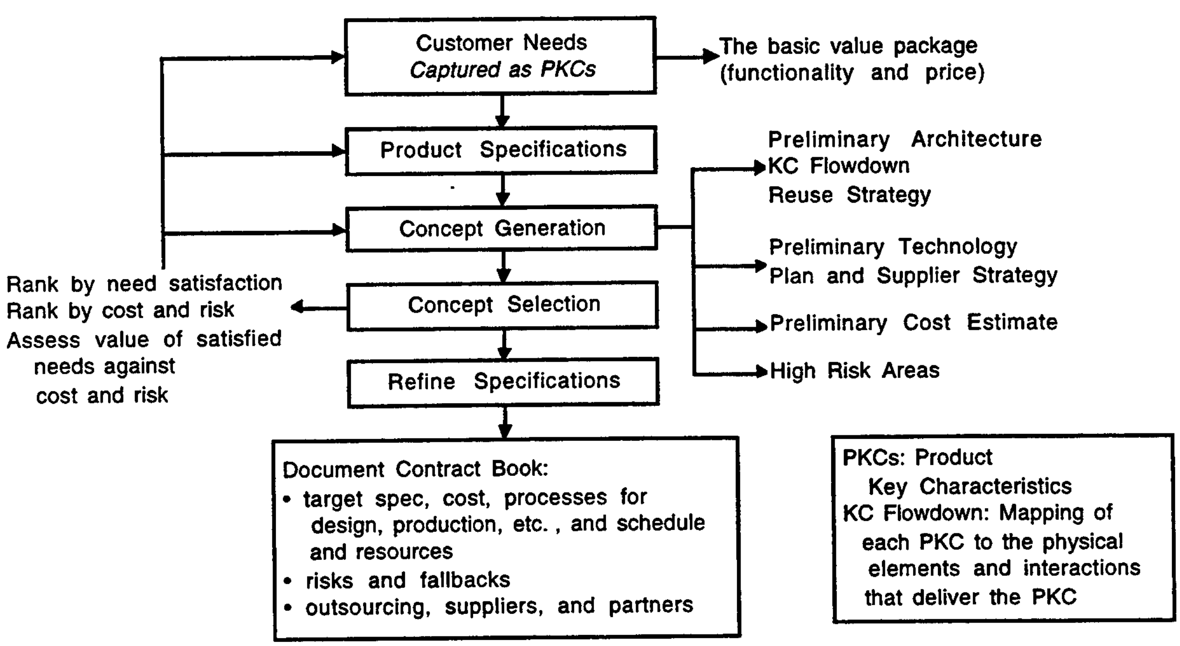


Figure 3-13. A description of concept design decisions (derived from Whitney [1997]).

The notion of IPD has expanded to incorporate broader representation from the strategic areas of the firm. A significant representation comes from supply chain strategists, who bring in issues like technology adoption and investment across the firm, selection of partners, and outsourcing of design and production. According to Fine [1998], who calls this *3D Concurrent Engineering*,[17] three critical interactions are paramount in this environment:

- traditional 2D integration of part design-fabrication process (involving design and producibility)
- production system architecture-logistics and materials system (involving producibility and supply chain strategists)
- product architecture-supply chain architecture (involving design and supply chain strategists).

The latter interaction is the target of this thesis, which I show requires the interaction of design, *producibility*, and supply chain strategists. Fine states that the IPT needs to reach architectural "concurrence", i.e. agreement that the architecture is suited to the needs of each, and the conflicts are understood. To communicate in this way about architecture, the IPT requires a clear identification of the architecture. This means a functional-physical mapping, and a relationship of this mapping to the processes, suppliers, technologies, etc. responsible for each physical element. Only then can the teams reach a concurrence on the architecture.

In order to mobilize a 3D IPD environment, tools are needed to draw attention to the impact that diverse decisions have on the architecture. Currently, even in IPTs, we observe a stovepipe mentality where decisions are made independently or in a sequence that makes coordination difficult. Add to that the natural barriers to communication among members of the different disciplines, and it can not be taken as given that these interactions will occur. 3D IPD will work when mechanized with tools that supply an agenda that forces the interactions to happen. Fine shows the architecture concurrence that is required: the IPT must identify the product architecture and rationalize it in the context of the broader strategy. To date the descriptions of concept design and the IPD philosophy as implemented thus far are insufficient to guarantee that the right analyses will occur.

Developing an architecture analysis method represents a distinct challenge because it must be appropriate to use in concept design where information is incomplete. IPD implementation in many companies has involved IPTs during concept design armed with analysis tools more suitable for use downstream in product development. This approach does not work because of the lack of detail in concept design. As a result, especially in the design of new, complex products, assessment of the proposed concepts by the producibility and strategy disciplines is rarely based on formalized tools. Without formal analysis to back their inputs, these disciplines historically have a difficult time in swaying the decision, though these decisions will have tremendous impact downstream and must be addressed in the concept phase. By contrast, engineering design tools, from system modeling techniques to computer aided engineering tools, are well developed in many industries to help judge the performance differences between

[17] I will use the term 3D IPD to be consistent with my terminology.

concepts even given only sketches or layouts. The level of sophistication of engineering design tools represents the goal for the development of methods to assess the broader issues, specifically a modeling technique of product architecture that the whole team can share.

3.3.2 Design Theory Relevant to Concept Design: Design Models, Systems Engineering, and Product Architecture

The following describes the three bodies of design theory from which the generalizations discussed in Section 3.2 were derived. Each is discussed in turn, followed by a summary of each in the context of the architecture matrix of Figure 3-2.

3.3.2.1 First Body of Literature: Models of Design from Design Theory

Models of design have evolved from research in both Europe and the U.S. While a broader review is possible [e.g. Finger and Dixon, Tate and Nordlund] I focus on three prominent models: Enhanced Quality Function Deployment (EQFD) [Clausing and Pugh, evolution from QFD in Hauser and Clausing], Axiomatic Design (AD) [Suh], and Pahl and Beitz [1977]. Pahl and Beitz is representative of other models from Europe that focus on methods used to develop physical solutions; these activities are called 'konstruktion' and are in the main the portions of design taught in undergraduate mechanical engineering design courses that form what Clausing [1994] calls 'partial design'. Tate and Nordlund state that this is common in European design models, so EQFD and AD represent a broader view more applicable to this research, focused on a more complete product development perspective. The Paul and Beitz approach is included in this discussion because it differs slightly in its representation of mapping from EQFD and AD, and has distinct ties to systems engineering and product architecture literature.

EQFD and AD prescribe more complete models of product development that start with capture of customer needs and show all the phases through design, production ramp-up, and product support. EQFD emphasizes all the steps equally to form a view of "total design." AD focuses on the mapping of functional requirements (FRs) to design parameters (DPs) and of DPs to process variables (PVs), and develops a mathematical basis for judging a design's mapping against a set of design axioms. Ulrich and Eppinger explain each of the steps of concept design (and the separate phase they call system level design) in detail. Because EQFD and AD form the most complete theories of product development, and because Ulrich and Eppinger describe the steps related to concept design in detail, the three works form the basis for my work that attempts to improve the prescriptive representations of mapping and decomposition.

3.3.2.1.1 Mapping and Decomposition in Design Models

AD prescribes the pattern of mapping and decomposition shown in Figure 3-4 to best represent decomposition in systems.[18] EQFD also captures this aspect of design of complex systems in stating that mapping is a recursive process at each level of the design - mapping occurs through many levels. EQFD explains how to use the Pugh concept selection process at each level.

[18] This is a pragmatic representation in that by making concept choices in the physical domain at each level, the scope of options for decomposition in the functional domain is somewhat limited and more manageable.

Pahl and Beitz also depict mapping from left to right, i.e. from functions to physical elements, but describe decomposition differently. In their representation, depicted in Figure 3-14, functional decomposition occurs completely apart from a physical solution. Functions must be broken down into sub-functions to sufficient levels where individual candidate physical principles can be identified that achieve each sub-function. The sub-functions are then mapped and linked with their interactions (inputs, outputs, flows of energy, signals, and materials, etc.) in diagram called a "function structure." Physical principles are then selected and a physical element for each sub-function is chosen. A "catalogue" approach appears to underlie this approach (and this is how I was taught it in my senior undergraduate design course) in that decomposition occurs to a level where some individual candidate physical solutions can be individually chosen and brought together into the full solution. This is indicative of a modular approach like VLSI in the signal processing domain. VLSI is distinctly different from complex mechanical design problems where performance on global measures is paramount and interactions are unavoidable due to the orders-of-magnitude higher power transmitted among the elements [Whitney 1996]. Note the difference between the AD and EQFD approach vs. a direct descent through a functional decomposition described here.[19] While Pahl and Beitz discuss an open attitude toward delivering function in more integral fashion, no mechanisms for how to confidently map function to many physical elements is provided.

3.3.2.1.2 Functional-physical Mapping Representations

Both AD and EQFD use matrix representations to relate (in the case of AD) FRs to DPs (equivalent to matrix 2 in Figure 3-3). Suh defines vectors containing the FRs and DPs, which can then be related by a matrix representation as shown in equation 3-1. An X in the matrix represents a relationship between a DP to an FR. Row n in the matrix shows how function n maps to the physical elements. A matrix would relate the functional and physical elements at each level of the hierarchy.

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X\,O\,X \\ O\,X\,X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \end{Bmatrix} \qquad (3\text{-}1)$$

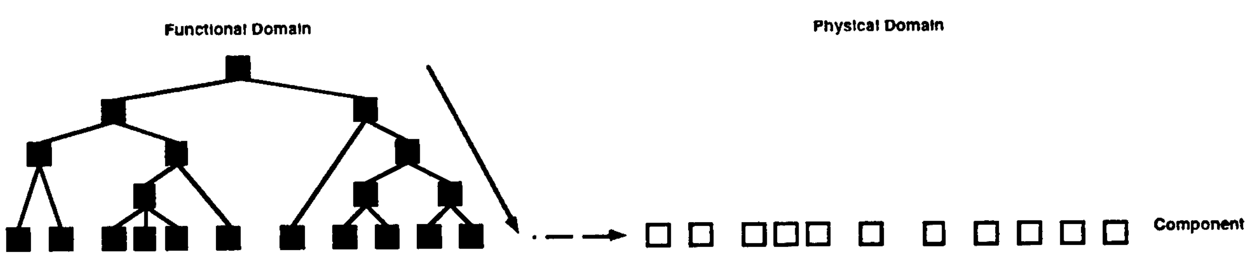


Figure 3-14. The Pahl and Beitz model: direct descent in the functional domain, then mapped to matching "catalogue" physical components.

[19] Pahl and Beitz describe several methods to accomplish a morphological approach to functional decomposition. In addition, in adaptive design, the existing physical structure could be the starting point for a functional decomposition, a hint toward a zig-zag approach. However, Pahl and Beitz do not discuss that this is a potential trap if the existing decomposition is either not optimal or not tailored to new requirements delivered in the adapted design, explained by Henderson and Clark [1990].

The matrices can be used to judge the degree of "coupling"[20] in the design. The first design axiom states that the best design is independent, equivalent to stating it is fully modular. The best design in a case where an independent design is not possible is "decoupled": that each parameter can be set independently if they are set in the right order.[21] If coupling exists, the best design exhibits the least amount of coupling (integrality).[22] EQFD does not state this explicitly but in personal conversations with Dr. Clausing he states that EQFD aspires to achieve this axiom. The axiom also applies to independence in the design of manufacturing processes, which has been investigated in many cases [multiple citations].

3.3.2.2 Second Body of Literature: Systems Engineering

Beginning in the 1950s with ballistic missile programs, the aerospace industry gave rise to a specifically designated field called systems engineering. Systems engineering principles are still evolving and there is no unified theory of systems that can be uniquely identified. Various systems engineering writings lead to a few broad trends in the tools. I draw much of this summation from an MIT course designed by Boppe [1995] that teaches a variety of systems engineering principles and practices accumulated from a variety of sources and his extensive industrial experience.[23] This section begins with a general overview of this body of literature, followed by a specific representation of systems from work in the field of information systems.

3.3.2.2.1 Mapping on the Work Breakdown Structure, Architecture, and Organization

I begin by reviewing systems engineering techniques for product management and developing the functional-physical mapping. First, systems engineering views a product in terms of what I will call a Work Breakdown Structure (WBS) whose elements are the systems, sub-elements, and individual parts of the product; the physical tree in Figure 3-1a is a WBS. Common system engineering processes begin with a functional decomposition followed by arrangement and interface definition in the context of a schematic block diagram (equivalent to a function structure as described by Pahl and Beitz). Second, functions are mapped onto the WBS (via the processes discussed below) and the interfaces among these elements are defined. Management of function delivery is conducted by attempting to track the contributors in the physical domain. Interface management among these physical elements is an attribute of systems engineering. The role is played by what is called a "system architect."

Systems engineering recognizes that some product requirements or attributes are integral characteristics because they are delivered in many WBS elements and their interfaces, and have to be managed from outside any distinct physical element. Figure 3-1b depicts this notionally. The approach to capturing these relationships can be twofold. First, requirements are "allocated", which is equivalent to decomposing the requirement and mapping the portions to elements (a

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[20] I use the term coupling to specifically refer to integral characteristics that share the same interactions between physical elements, while Suh uses the term to mean "integral" characteristics that are affected by the same design parameters, so the characteristics can not be designed independently.
[21] The analogy is a linear system that is solved by Gaussian Elimination.
[22] An additional issue is that this axiom applies to the relation of FRs and DPs only, and global "constraints" like weight are not identified as FRs, according to AD. By definition, constraints "do not have to be independent" of the DPs.
[23] This reinforced my experience in a short course on systems engineering that I received as part of my professional training [SMDC, DSMC].

divide and conquer philosophy that assumes no stray contributors will upset the plan). However, a second possibility is the potential for "derived" functional to physical relationships that should be recognized as inherent to the physical solution. That is, a physical solution will create a distinct set of requirements that will need to be managed. In this way, systems engineering shows an apparent openness to a two-way recognition of the functional-physical mapping, and therefore to integrality. However, mapping relies solely on an expert process that assumes the systems architect can uniquely map a function to specific elements (and none others), or recognize derived mapping that is inherent in the physical solution.

The second portion of systems engineering literature deals with deciding the physical arrangement and decomposition. This portion of the literature discusses techniques for how the system should be decomposed to *minimize* integration across sub-systems, i.e. to achieve a modular solution. The foundation was established in theoretical work on the interactions of decomposed systems [Alexander]. A body of system engineering heuristics has been developed that in the main is based on experience [Rechtin]. To summarize, the heuristics espouse modularity, that complexity should be driven to the modules and away from the integration. Little in the form of systematic methods to achieve modularity are offered, though the heuristics do attempt to capture findings from a broad range of systems.

The organizational issues associated with this approach to managing systems are discussed in Section 3.3.2.3.2.1.2.

3.3.2.2.2 A View from Information Systems

Hatley and Pirbhai [1988] develop a system specification technique for information systems with four aspects that differ from the mainstream systems engineering literature described here. First, functional decomposition is portrayed like the zig-zag pattern shown in Figure 3-4. Derived requirements are not recognized explicitly. Second, because their work is tailored to dealing with information flows only, they state that functions can be mapped to physical elements by directly relating what information must be shared among the elements. In this case an mapping process from functions to physical and logical elements works because the designer is expected to know what interactions - the information flows - among physical elements must be mapped; i.e. they are dictated and incidental interactions are not typically encountered. And, they are aided by the fact that the type of interface in general will not alter the interactions, or information shared, among the elements. Third, Hatley and Pirbhai do not make any reference to modular representing an ideal. In fact, the measure of merit of decomposition is minimizing the number of computational tasks in each physical element, even if a great deal of information flow (i.e. integrality) among elements results.

The final difference is most distinct. Hatley and Pirbhai draw a difference between the information flows and physical interfaces in the physical domain. Figure 3-15 shows their physical system architecture. At the top is an Architectural Context Diagram, which is in effect a WBS with the different branches being the user interface and four processors: input, output, maintenance, and the main processor. The lower level is a set of dictionaries that contain information documenting the detailed content of these diagrams.

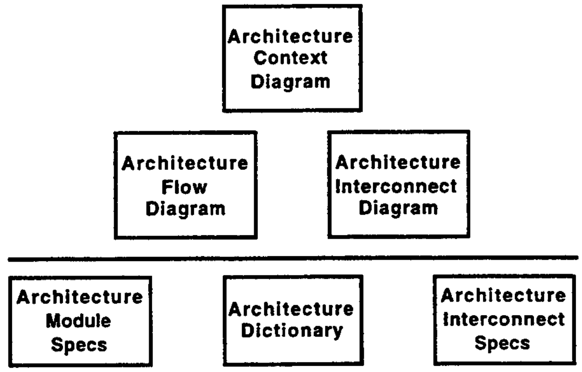

Figure 3-15. The Hatley and Pirbhai physical architecture model for information systems draws a distinction between the flows and interconnections that is typically not represented in systems engineering models [Hatley and Pirbhai].

The distinction lies in the middle level of the figure where functions and physical interfaces are shown in two different elements. One is the Architectural Flow Diagram, which captures the information flows between physical elements. Second is the Architectural Interface Diagram, which captures the physical interfaces between the elements. The flows and the physical interfaces are recognized as being distinct.

More common to systems engineering models is just a depiction of the interfaces, which is implicitly assumed to manage any functions shared among the physical elements. The assumption is that if the interfaces are tightly controlled, function will be delivered even if we do not explicitly recognize which functions are delivered in which interfaces. The view in Figure 3-15 is assisted by the fact that the information flows are in general not altered by the interfaces. We have shown that in mechanical products the choice of interfaces does alter the interactions. However, this subtle difference in the Hatley and Pirbhai view will be revisited in Chapter 8 to draw analogies to the chain representation in the context of product data models, where it is useful to find a way to distinguish between interaction information (chains) and interface information.

3.3.2.3 Third Body of Literature: Product Architecture

As stated above, product architecture is the term now given to the scheme by which functions are mapped to physical elements and the definition of interfaces among the physical elements. From this definition we see that product architecture unifies elements of design theory and systems engineering, along with the related strategic issues. The following revisits the architecture definitions introduced above and opens the discussion to the broader strategic issues reflected in the architecture literature.

3.3.2.3.1 Limitations When Applying the Existing Definitions to Integral Characteristics

Product architecture is presented as open to modular and integral options [Ulrich and Eppinger, Ulrich], recognizing the merits of each. However, the mapping process described is similar to that in the design theory and systems engineering literature, and is therefore subject to the same critique. Ulrich and Eppinger describe three steps that are drawn from design theory and systems engineering. Architecture is set as defined by 1) arrangement of functional elements, 2) mapping function to components, and 3) definition of interfaces. In this view functional

elements are grouped into sub-systems using a tool like a function structure or schematic block diagram, a physical solution for each function is selected, and interfaces among these groupings are identified. There is a clear and heavy influence of Pahl and Beitz and the interface control philosophy of systems engineering. The premise is that the mapping can be selected, though Ulrich and Eppinger recognize the possibility of "incidental" interactions that are like derived interactions described in systems engineering. Once again, formal methods for attaining this mapping are not provided, so methods are needed to aid this heretofore expert process. The process is applicable to modular systems where the intent is to deliver each function in one element, but does not readily support the integral case or any case where physical domain decomposition occurs.

3.3.2.3.2 Architecture Definitions are Immature

The definitions as posed meet Ulrich's stated goal of unifying concepts from design theory, systems engineering, and product development strategy. However, the language of architecture is immature in that 1) most products can neither be solely identified as modular or integral, and 2) a single system may appear modular at some level of the hierarchy while appearing integral at other levels. A true measure of a product's architecture is typically mixed, and therefore does not fall into any one category. The following expands on these two issues of immaturity.

3.3.2.3.2.1 Modularity/Integrality is a Spectrum

First, the idea that a product is either modular or integral is immature when applied to real products, so architecture is a relative property of a product [Ulrich and Eppinger]. Real products implement many functions, some in a modular character, others in an integral character, and some are coupled. Architecture is therefore a spectrum and must be depicted as such.

The ability to distinguish whether an *individual* sub-element has a modular or integral character has a direct link to many manufacturing and strategic decisions. For this reason architecture should be captured at the level of the individual characteristics, then summed up to a product characteristic. The following definitions support thinking of mixed product architectures in terms of the individual characteristics:

- *modular characteristic*: a function delivered in a distinct element of the decomposition - no interactions across the WBS
- *integral characteristic*: a function delivered across two or more elements and their interactions
- *coupled characteristics*: two or more functions delivered in the same interactions across elements[24]
- *modular element*: a sub-assembly or component that delivers its function all by itself and does not participate in the delivery of any other functions
- *integral element*: a sub-assembly or component that participates with others in delivering a function, or that delivers two or more (possibly coupled) characteristics

[24] Note: two or more modular characteristics can be delivered in one element, we don't think of these as coupled unless there are interactions across elements.

The matrix presented in Figure 3-2 separates out the individual function character in the top row and the combined character of the product in the bottom row, creating a more complete language that addresses this issue.

3.3.2.3.2.2 The Hierarchical Nature of Systems

The hierarchical nature of systems discussed in numerous works guides how to expand the modular/integral designation into a spectrum. Real systems have hierarchies and the functional to physical mapping varies at each level. At one level function may look modular, e.g. if it is delivered in a single system. But it could be integral below that level, e.g. if it is delivered in several modules of that system (this satisfies the system engineering heuristics [Rechtin], and the design axioms [Suh] if "functional decoupling", as described in Section 3.3.2.4.1, is maintained). In other cases, at one level a function may be shared among systems so it appears integral, but within each system the function looks modular if it is delivered in a single element (a case not considered in any of the literature). Either case is integral if we use the criterion "mapped to several elements of the system." Which is more integral?

Figure 3-16 shows four cases of the mapping of integral characteristics that shows a two dimensional character of the mapping. The example in Figure 3-16a looks integral at any level. The example in Figure 3-16b looks modular at the system level but integral below. The example in Figure 3-16c looks modular at the module level but integral below. The example in Figure 3-16d looks *integral* at the system level but *modular* below in any one of the systems. I call the horizontal character "span" and the vertical character "height", and the two combine to measure the relative integrality of how a function is dispersed among the physical hierarchy. Section 4.3.1.1 describes how span and height are measured using chains.

All of these correspond to real examples in the cases I studied. For this reason architecture is a two dimensional mapping attribute, not just an attribute measured by the number of elements to which a function is mapped, as in the basic definition.

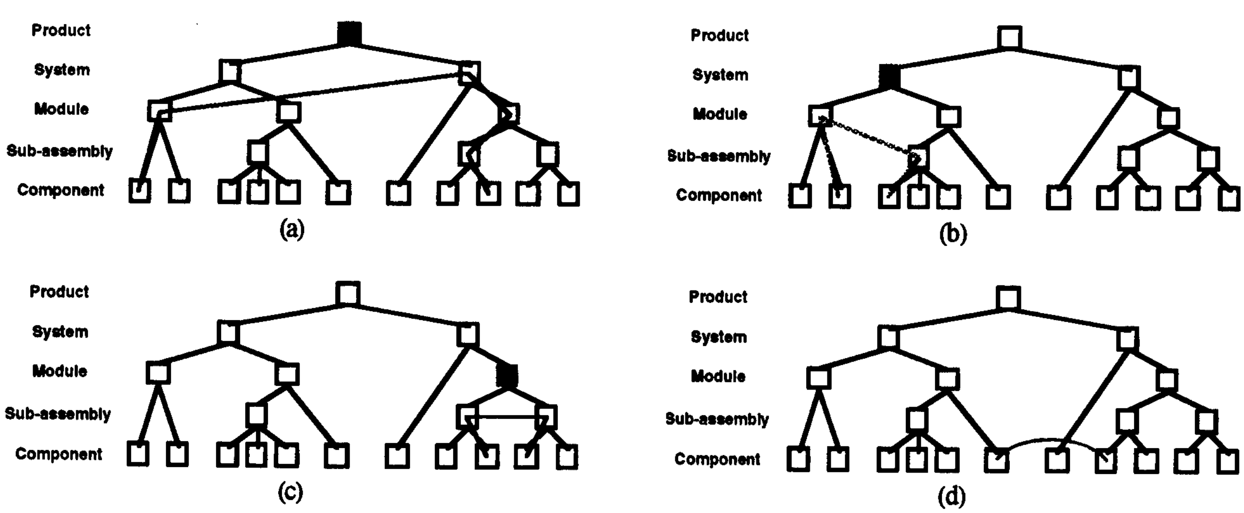

Figure 3-16. Four examples of how integrality varies when viewed at different levels of the physical hierarchy. The "span" and "height" characteristics are described in Section 4.3.1.1.

3.3.2.3.3 The Alignment of Organization, Strategy, and Product Architecture

Product architecture is of intense interest in the management community as well as the engineering community, as indicated in the 3D IPD theory [Fine]. The engineering community traditionally thinks of 2D IPD - teaming of design and manufacturing - and considers IPD to enable a *concurrent process*, i.e. overlapped tasks, rather than the emerging emphasis on *concurrence*, or agreement among all parties with a stake in the design. More emphasis on the latter is needed for 3D IPD to work. Designers do not own architecture, nor does the producibility domain. Architecture is a product of the decisions of all members of the IPT, technical and non-technical, and a poorly coordinated architecture has long-term impact on interests of all of these groups.

The following outlines two issues that impact architecture from the strategic viewpoint: its relation to outsourcing and supplier management, and its relation to development of new architectures. One objective is emphasized throughout, that in order to coordinate architecture and strategy decisions, the level of architectural discernment needs to be *at the level of the individual element, not just at the level of the product as a whole*. Individual elements may be a whole system that will be outsourced as part of a teaming arrangement, or an individual part that will be outsourced to a supplier. So, these decisions begin early in product development and continue throughout, emphasizing the need for an architecture focus during concept design when the decisions start.

3.3.2.3.3.1 Corporate Strategies toward Lean, Outsourcing, and Tiered Supply Chains

Much of the emphasis on make/buy decision making, or *outsourcing*, can be traced to the definitive work on the product development approaches that set Japanese automotive firms apart from the rest of the world in the 1980s [Clark and Fujimoto]. These product development approaches were combined with production practices in defining the "lean manufacturing" paradigm [Womack et.al.]. A major finding from this in-depth international auto industry study was on the major impact that reduced *project scope* - the percent of new design being conducted by the lead firm - had on reducing development time [Clark and Fujimoto]. Faster development time creates distinct competitive advantage [Wheelwright and Clark] and is increasingly becoming the focus of many companies and the Government today. Aerospace companies in the 1990s also have implemented outsourcing strategies that follow the lean paradigm, though not necessarily to reduce product development time.

3.3.2.3.3.1.1 The link between Outsourcing Strategy and Product Architecture

To reduce project scope, the best companies carefully choose "black box" components, those that can be developed as separate entities by highly competent suppliers. Components that have many interactions and therefore can not be developed as separate entities must be controlled in-house, either to detail-level or to some interim amount of involvement in integration, thus setting the scope of the development effort. In order to treat a component as a black box, its interfaces must be limited and have a well-defined role in delivery of function; it must be *modular*.

The relative integral character of a physical element and its suitability for outsourcing are inseparable. Several recent articles tie the outsourcing decision to a firm's core capabilities,

saying that which is core should be kept in house and nurtured for its strategic advantage [e.g. Venkatesan]. There are many views of what should be deemed core. The discussion expands when the nature of dependency between buyer and supplier is emphasized. The buyer must be well aware of why the outsourcing decision is necessary - is the need for *capacity* or for *knowledge*? If the need is knowledge, and if that knowledge is of a strategic "integral" element in the system or necessary to develop the system, this presents a high risk position because the supplier could leave the arrangement, taking an integral element with them that leaves the system integrator unable to deliver some function of the product [Fine and Whitney]. Fine and Whitney capture four scenarios involving architecture and outsourcing choices in a Matrix of Dependency and Outsourcing.

This emphasizes the need for a way to clearly identify what functions in a product are delivered in integral characteristics and which are decomposible, i.e. more modular in character. Architecture is not simply a product attribute, it is an attribute describing how each function is delivered. The issue of finding a coordinated architecture, manufacturing approach, and strategy appears to be most critical in industries where integral designs are the best solution technically but outsourcing and platform strategies better suited to modular products are the desired, or perhaps required, strategy. The JSF case study in Chapter 7 is a prime example of this conflict. Note that this conflict is represented in Fine and Whitney's Matrix of Dependency and Outsourcing, where they assume there is a choice but in the JSF case this was found to be a dictated conflict. In this case the IPT requires a central framework around which to concurrently create a product architecture that allows them to exploit the strategy while maintaining competitive product performance.

3.3.2.3.3.1.2 The Tiered Supply Chain

Product development is typically organized and managed around the WBS, with teams allocated to physical elements. Integration among the elements is the responsibility of the systems group, who often may not have the authority to order changes in any one system when incompatibility is present. Teams are assigned to the lowest defined elements in the decomposition and rarely take responsibility for integration unless these issues are distinctly portrayed among the teams. In my and others' observations we see a distinct lack of system awareness among teams assigned to the individual elements. When these elements share in the delivery of integral characteristics, this presents a distinct risk.

Most supply chain networks in industry today occur in tiers that follow in large part the WBS; i.e. the suppliers report directly to the company to which they ship parts instead of the overall prime or final assembler.[25] Tiered supply chains dominate the landscape in the automotive and aerospace companies. The system suppliers typically manage the module suppliers, who manage the sub-assembly suppliers, etc. In its outsourcing plan the prime designer and integrator chooses whole systems and modules that will be built by other companies, and portions of the

[25] This is a common solution to the lean push for "fewer suppliers." Responsibility for lower tier suppliers is pushed onto the tier immediately above, as opposed to management of the complete chain by the prime.

systems and modules to be managed directly in-house that will be outsourced to suppliers that will report in the prime's branch of the tiered supply chain.

Unfortunately, teams like this often do lack a system view. For example, individual element designers and producers often to not recognize how their element shares delivery of a function with other elements. The added burden of a tiered supply network puts communication about integral characteristics in great peril. It is for this reason that integral characteristics are poor candidates for outsourcing. When outsourcing exists among the elements of an integral characteristic, explicit emphasis must be placed on integrating those suppliers. This must be recognized at the time when the decisions are made to either alter the strategy or recognize the inherent risk.

3.3.2.3.3.2 Development of New Architectures and Product Platforms

Two important insights into the development of new products are centered on the type of innovation that is required to remain competitive and platform strategies. The literature contains a stream of works that have captured insight into technological evolution by following innovation in several industries. One type of innovation - *architectural innovation* - stands out in particular because it does not incorporate sweeping new technologies, just a critical re-integration of components to deliver a product with new advantages [Abernathy and Clark]. Utterback's [1994] discussion shows that the "dominant" design[26] integrates technologies and components that already exist, but arranges them in such a way to best capture the customer needs. Further, the organizational skills that make a firm the leader in one phase of a product betray it when architectural change in that product is necessary; the firm organizes itself around its architecture and is incapable of seeing the same product components with a new and creative set of interfaces to create the new architecture [Henderson and Clark]. Utterback's categorization of assembled and non-assembled products is useful as he shows it is much more difficult for a firm to invade a market with a new non-assembled product than it is to invade and capture market segment with as assembled product similar to the current market leader but in the form of an improved architecture. Christiansen et al [1992, 1996] have developed related arguments based on extensive research of the rigid disk drive industry. Being able to recognize architectural change opportunities is critical to both the attacking and the established firm.

The second insight is in the management of the firm's development portfolio. Wheelwright and Clark [1992]developed a framework for mapping the development efforts of a company in terms of product and process innovation, labeling new products as derivative, breakthrough, and platform in order of increasing innovation. A firm must choose this strategy carefully to best utilize its limited resources, talents, and manufacturing capacity. Sanderson and Uzmari [1996] and Meyer and Lehnerd [1997] emphasize the competitive advantages of well-conceived platforms that allow for numerous derivative products to be rapidly introduced to new markets with limited effort. The effect of a coordinated architecture and strategy is evident in that a well defined modular architecture will allow for much easier product change than would an integral

[26] A dominant design is "the one in a product class that wins the allegiance of the marketplace and innovators must adhere to if they hope to command significant market following." [Utterback]

architecture, but if certain attributes are tailored to the different variants then integral characteristics could optimize that performance. This trade space is complex and requires a clear depiction of whether each unique function is delivered in an integral or modular character in the decomposed product.

3.3.2.4 Relations Between Design Theory and Product Architecture

This section briefly summarizes the concepts depicted in the different bodies of literature in the context of the matrix presented in Figure 3-2. Figure 3-17 summarizes the links between them. The terminology and organization of the four prominent cases presented in Figure 3-2 is intended to improve the unified language that is the intent of the product architecture literature, and to draw attention to architectures with integral character.

3.3.2.4.1 Axiomatics - uncoupled, decoupled, physically coupled, functional coupled designs

The first design axiom states that the best design is independent, meaning all functions are delivered by a unique design parameter and is indicated by a diagonal matrix relating the FRs and DPs. This corresponds to the upper left box of Figure 3-17. When an independent design can not be obtained, the best design is one that is decoupled as indicated by the triangular matrix of equation 3-2. This corresponds to the lower row of Figure 3-17, though Suh draws an important distinction in the type of coupling. If multiple DPs are contained in the same physical part (corresponding to the function sharing case at the lower left of Figure 3-17), but the FRs are independent in those DPs, then the design is *physically coupled* but *functionally decoupled*; this situation satisfies the axioms. The matrix relating the FRs and DPs will be either independent or decoupled, though the matrix relating the FRs to the physical parts could look like equation 3-3. Alternatively, the best remaining solution exhibits the least amount of coupling, where coupling is represented by a matrix between the FRs and DPs that can not be changed into a triangular form like the one in equation 3-4. This corresponds to all cases in the upper right of Figure 3-17 and functionally coupled cases in the lower row.

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \end{Bmatrix} = \begin{bmatrix} X & O & O \\ X & X & O \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \end{Bmatrix} \qquad (3\text{-}2)$$

Functional Elements		Physical Elements: One/one or a few	Physical Elements: Many
	One delivered in:	A: modular [Ulrich 95] D: independent [Suh]	A: ("one-to-many" integrality)? or "holistic" [Ulrich and Ellison 97] D: coupled **Chain**
	Many delivered in and shared by:	A: "many-to-one" integrality [Ulrich 95] or "function sharing" [Ulrich and Seering] D: coupled or decoupled (physical/functional) [Suh]	A: "mixed" architecture [Ulrich and Eppinger] D: coupled **Coupled Chains**

A: Architecture Literature, D: Design Theory Literature

Figure 3-17. Links between the bodies of literature in the context of the matrix in Figure 3-2.

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} XXOO \\ OOXX \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \\ DP4 \end{Bmatrix} \tag{3-3}$$

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \end{Bmatrix} = \begin{bmatrix} XXO \\ XXO \\ OXX \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \end{Bmatrix} \tag{3-4}$$

3.3.2.4.2 Architecture and Function Sharing

Figure 3-17 also captures the definitions from the architecture literature and captures some of the conflicts in the literature. The upper left corresponds to the modular case. The upper right corresponds to the integral case, where one function is mapped to many elements and their interactions; in fact none of the architecture or systems engineering literature has a specific name for this though it has been alluded to as "one-to-many integrality" [Ulrich] or "holistic" [Ulrich and Ellison]. This case is said to be acceptable when it optimizes performance on some global measure. The lower left is the function sharing case (that Ulrich called "many-to-one" integrality), again representing an approach to optimize performance on a global measure by combining many functions into a single part, or perhaps related features of the same part (which would create functional coupling). The lower right is not discussed directly in the architecture language other than the reference to "mixed" architecture by Ulrich and Eppinger.

3.3.3 Review of the Role of Mechanical Assembly in Product Development

The final portion of the literature that requires a review is that covering assembly modeling and analysis techniques. Recall that my work focuses on mechanical assembly, where an established modeling and mathematical basis has potential application in a prescriptive model of concept design. Also recall the C-17 nacelle example described in Chapter 1, where the chain graphically depicts the elements and interactions that impact a product-level attribute that is traceable to function, a clear indication of the functional-physical mapping. The following describes several types of assembly models, followed by a review of the underlying mathematics of how relative location is achieved and variation propagates in assemblies. Chains have their roots in these two bodies of work. In this review I include observations about these tools that lead to the topic of Chapter 4: development of the chain procedure and metrics applicable to concept design. Appendix B includes a summary of a broader review of Design for Manufacturing and Assembly tools, which I found to lack direct application in concept design.

The notion that the consideration of assembly issues can give structure to broader design team decisions has been posed and explored in later design phases [e.g. Whitney 1988, Whitney 1990, Nevins and Whitney, Behan] but has not yet been exploited during concept design. In the C-17 example I described the decisions made years earlier that reflected on the misalignment of the inlet and engine bay door, a physical attribute that impacts functions, and is affected by several other elements and their interfaces. How early in product development could this integration issue have been recognized? Could this architecture problem have been recognized in concept design when the incompatible decomposition and supply chain were created? Could the chain tool

presented in this thesis have helped to recognize this problem then? The goal here is to convince the reader that chains have a sound basis, and the goal of the next chapter is to describe how this basis can be applied in concept design.

3.3.3.1 Assembly Modeling

An assembly model is a representation of the product in the context in which it is built, i.e. in the connections between its parts. Whitney [1997] lists six types, culminating with the Datum Flow Chain concept developed by Mantripragada [1998]:

- Bill of Materials (BOM): a list of all the parts (in no particular order)
- Structured BOM (SBOM): a list of all the parts in a hierarchy that represents the components, sub-assemblies, etc. in which they are assembled. This is sometimes called a Manufacturing BOM (MBOM), Product Breakdown Structure (PBS) or WBS as used throughout this thesis.
- A liaison graph [Bourjault]: graphs in which parts are represented as nodes, joints between parts as arcs
- Ordered liaison graphs: the arcs have arrows to depict an order in the process
- Attributed liaison graph: the arcs have constraint or feature information
- Ordered-attributed liaison graph: a "Datum Flow Chain" (DFC), described in Section 2.2.2.

Each of these models has different attributes that fill different needs. A SBOM/MBOM/WBS carries organizational implications by representing not only what is built but also by whom and the relationship to the hierarchy, and can be used to measure the cycle time in assembly via the critical path. Chains are depicted in assembly models based in graph theory. These graphs depict parts as nodes and contacts between the parts as arcs in the graph. All graph techniques carry interconnectivity information that, though it relies on the definition of parts in order to capture liaisons, allows variation propagation to be represented. The DFC carries the chain logic presented in the next section by capturing just the liaisons that affect dimensional relationships (called the *mates*) and is therefore a vehicle to understand both datum logic and allows application of the variation techniques described below [Mantripragada et al, Mantripragada and Whitney]. Early roots are traceable to work in the fields of robotics by Simunovic [1979] and assembly modeling by Lee and Gossard [1985]. Chapter 4 describes the chain representation applicable for use in concept design that derives from these established assembly models.

3.3.3.2 Mathematical Background of Chains in Coordinate Transform Mathematics and Tolerance Chains

Chains have established physical and mathematical bases in the concept of *coordinate transforms*: the position of a feature on any part of an assembly relative to some base reference frame, or relative to a feature on another part, lies at the end of a chain that describes how the parts are connected to each other. This describes the problem of interest here. We are interested in the relative location of features, generally on different parts, where the parts are often members of different branches of a WBS, and we would like to identify all the elements and interactions that affect the final relative location of the features. This thesis does not develop the mathematics but leverages the fact that the techniques are so well developed that application of

the chain approach early in product development leads to quantitative analysis that will be conducted downstream.

The coordinate transforms technique uses a matrix containing position (3x1 vector p in equation 3-5) and orientation information (3x3 rotation matrix R in equation 3-5) to transfer the coordinate reference frame between two points.[27] These points can lie at the origin of datums on assemblies and parts, at features of apart, or any point of interest in space. Matrix multiplication is used to transfer between several points; e.g. to transfer from point 1 to 3 through 2, a transform is captured from 1 to 2 and from 2 to 3, and the two are multiplied to get the full transform from 1 to 3. The mathematics permit one to calculate the location at point 3 if one knows the location 1 plus information about how 2 is related to 1 and how 3 is related to 2. We keep track of each contributor by representing each transform with a "link" in a "chain." Figure 3-18 illustrates the idea in the context of an assembly where we are interested in the relative position of parts a and b, where each link is associated with a matrix T_i.

$$T = \begin{bmatrix} R & p \\ 0^T & 1 \end{bmatrix} \tag{3-5}$$

It is important to note that the same mathematics are viable for calculating the *variation* of the position of the feature of interest as well as the nominal, so in assembly we can calculate the expected variation in the relative location of two features given tolerance information about the parts, especially about the features and geometry at places where they assemble to each other. The content of the matrices changes to errors in position and orientation [Whitney et al 1994]. The chain looks the same whether we are representing nominal position or variation; the latter case just requires more information. Variation analysis in assemblies is an active field, with many current efforts summarized by Chase and Parkinson [1991]. Statistical variation techniques [Bjorke] or closed form solutions that assume Gaussian variation distributions [Veitschegger and Wu] are both applicable to this method, the latter applied directly by Whitney et al. The

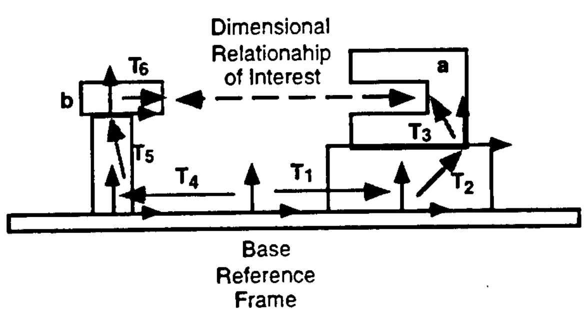

Figure 3-18. Nominal build up of relative part positions in an assembly. T_i represents each 4x4 matrix transform that relates the position of the successive part in the assembly, starting from the base. The dimensional relationship of interest is the relative position of two features on different parts. The chain is a graphical representation of the transforms that affect the end dimension of interest.

[27] The underlying mathematics are summarized in Paul [1981]. It should be noted that this is the underlying mathematics of computer graphic systems, so the assembly technique has direct connection to the nominal geometry in a CAD system [Whitney 1997]. The bottom row provides scaling information used to create perspective in a computer graphic image.

statistical technique and coordinate transforms is the basis of a commercial software package called Variation Simulation Analysis (VSA) that is evaluated as part of Chapter 4.

Therefore there are two key, established mathematical concepts. First, dimensions in assemblies are delivered in chains, whose links lie both within elements and in the interfaces of elements. These chains can be represented by a simple set of 4x4 matrices and matrix mathematics can be used. Second, variation propagates along the same chains and can utilize the same matrix techniques.

3.4 Chapter Summary: A Prescriptive Design Model and Two Research Themes

This section bridges the review conducted in this chapter and the topics in the next four. First, I show the framework for an IPT to make architecture and decomposition choices during concept design. Second, I describe two research themes and how they are developed in the subsequent chapters.

3.4.1 A Prescriptive Model with a Framework for Architecture and Decomposition Choices

From the discussion in Sections 3.2 and 3.3, I derived three main requirements for a prescriptive model that utilizes chains to depict the functional-physical mapping associated with physical decomposition influence in integral designs:

- the mapping must be derived from a systematic procedure for capturing chains in concept design
- the results must show the differences in the mapping for different physical decompositions with metrics that can be utilized during concept design, and
- the mapping must support a 3D IPD approach to identifying and selecting the architecture that results from the mapping.

The systematic procedure and metrics are described in the next chapter. Here it is useful to develop a framework for architecture and decomposition decisions.

The first question is: given that design theory and system engineering recommend that decomposition occur in the functional domain, what forces, decisions, and IPT participants cause decomposition to shift to the physical domain? I categorize three main types. The first type occurs in the domain of the designers (the group that formulates the physical design), specifically in their choices of how functions are achieved in the physical system and sub-systems. The second type is in the domain of the producibility group (those who develop the manufacturing and assembly process), in their identification of assemblies and sub-assemblies suited to the manufacturing system. The third is in the domain of the strategists (the members of various groups relating the business strategy to the specific product being designed), for example in their determination of which parts and sub-assemblies will be outsourced, in what technologies the company should invest, and how a particular product should be decomposed to satisfy a broader platform strategy for many products. All three decisions are crucial elements of concept design

and interact highly, so the prescriptive model must seek to coordinate an IPT involving these three disciplines during concept design.

The second question is: how should the IPT use the knowledge gained from insight into the architecture? Because this knowledge needs to be generated during concept design, the IPT should use the it to mature the candidate concepts and as input into concept selection. To mature the concepts, feedback in the process is required where each group rationalizes its input and attempts to reach a level of concurrence. In addition, different decompositions for each concept should be considered that could better achieve the desired architectural outcome.

Figure 3-19 shows an architecture and decomposition analysis framework that captures my approach to the problem. The three types of decisions that affect decomposition must be gathered into a set of candidate physical decompositions. The integral characteristics, and hence the architecture, that result from decomposition must be identified and assessed for integration risk. Feedback among design assumptions, strategy, and decomposition must be supported so a low risk solution that best meets the needs is developed.

3.4.2 Two Research Themes

The concepts from the literature presented here form the basis for this research along the two themes. Chapters 4 and 5 develop the use of *chains as a functional-physical mapping representation of integral characteristics* that indicates integration risk. I apply the assembly modeling concepts to create a consistent mapping procedure for chains (and various representations of one and many chains), develop a set of metrics to compare the chains of different candidate physical decompositions, and demonstrate the use of the procedure and metrics in the context of several examples. Chapters 6 and 7 develop *a 3D IPD representation of how chains fit in the concept design phase*. The method is demonstrated in the context of a deep case study.

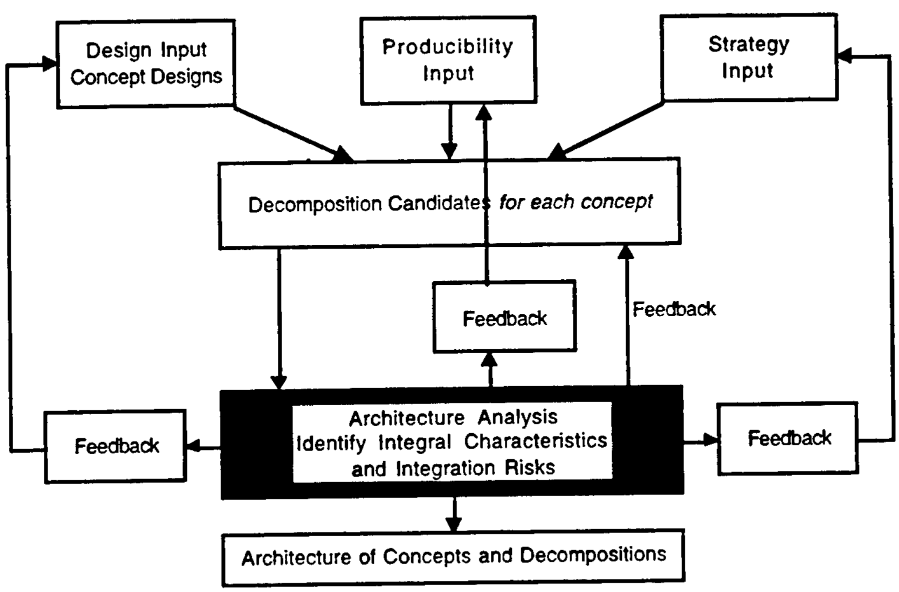

Figure 3-19. An architecture and decomposition analysis framework among design, producibility, and strategy decisions that impact decomposition.

My research will further the product development representations reflected in the theory by more accurately depicting integration issues in the development of real products and real decision processes. The issue is most critical in industries where integral designs are the best solution technically but principles better suited to modular products are the desired strategy, e.g. highly decomposed products, rampant outsourcing, and product platform development. Without improved insight into product architecture, it will be difficult for these industries to exploit these strategic sources of competitive advantage while maintaining competitive product performance. Careful distinction between modular and integral items will improve early development decisions in this type of product; my research will address this need.

The design models are greatly enhanced with systematic methods that a design team can confidently apply to map functions to their physical elements when integral or mixed approaches are taken. This mapping lies at the heart of design models but in fact may occur as a by-product of other decisions, namely physical decomposition. Without a firm grasp on this mapping, the team will not accurately be able to gauge the relative integral character of the design and will face consequences downstream when the integration risk reveals itself. Chains are applied to satisfy the need for systematic functional to physical mapping techniques, an extension of the application that complements the design models and opens them to the broader issues of product development.

4. Chains

This chapter explores the first research theme: using chains to reveal the integral characteristics and to estimate the integration risk of the product architecture as it is created during concept design. Chains are intended to permit the IPT to depict graphically how important Key Characteristics (KCs) will be delivered in each decomposition, to specifically identify those KCs that are delivered in integral or coupled integral ways, and to analyze the integration risk associated with the integral characteristics. Chains allow the IPT to systematically design the product architecture early in concept design when there is the greatest opportunity to control the outcome. This insight into the architecture can be documented as input to concept selection, and as the basis for risk mitigation activities downstream in product development.

Figure 4-1 shows the decomposition and architecture analysis framework and highlights the steps that are developed in this chapter. Section 4.1 defines chains, principles for capturing chains that

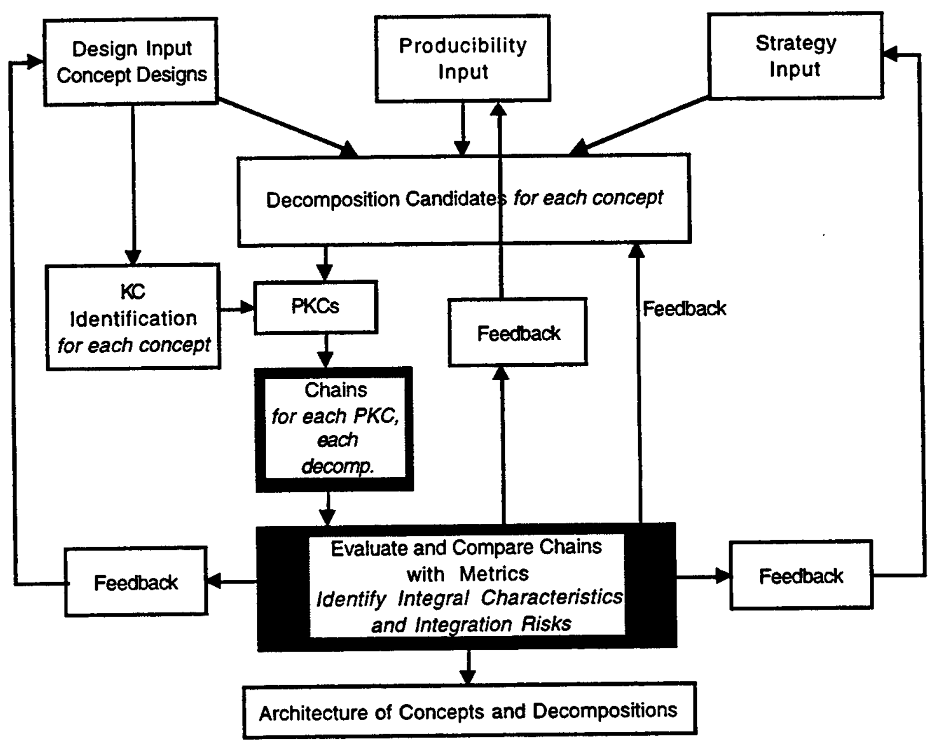

Figure 4-1. The decomposition and architecture analysis framework, with the highlighted steps representing the two parts developed in this chapter.

guide a simple chain capture procedure, and rules for depicting chains, and relates chains to KC terms used in the remainder of the thesis. Examples of the graphical representations are shown. Section 4.2 develops six properties of chains, including an informal description of a general chain capture procedure, that make them applicable to the decomposition and architecture analysis framework that is to be implemented in a multi-disciplinary IPT during concept design. Section 4.3 describes six metrics of chains that can be applied during concept design to identify the integral characteristics and assess their integration risk. In real products the IPT must deal with many chains; Section 4.4 introduces a matrix representation that can be used in this more complex environment. Section 4.5 describes how chains can lead to focused quantitative assembly variation analysis sooner than is typically seen in current design practice. Section 4.6 summarizes the chapter by explaining how the architecture of a candidate concept and decomposition should be documented based on the chain analysis.

The fundamental issue is that *some functions are delivered in chains*. Functions delivered in chains are integration intensive and therefore must be identified and characterized in order for the IPT to properly understand a candidate architecture and its integration risks. Chain representations provide an illustrative map of all physical elements, and the associated process steps and suppliers, that affect a product attribute that delivers function. This definition of chains spans product design, manufacturing, outsourcing, technology strategy, assembly, and final product quality, and, as such, helps the IPT to evaluate the concepts from this broad, but necessarily broad, point of view. This general definition applies to elements that operate in any domain, not just mechanical, that share delivery of product function.

The question that remains is: on what do we base the *content* of chains beyond just the judgment of the individual? In this research I focus on the mechanical domain basis of chains. In the mechanical domain there are established *principles*, based in the transform mathematics and assembly models introduced in Section 3.3 and developed further in Section 4.1, *for how dimensional relationships are achieved in assemblies*. Ultimately many types of functions mapped to integral characteristics are in turn delivered by the relative positions - a set of dimensional relationships - of features on different parts. Dimensional relationships are function carriers. When we analyze the integration risk of the dimensional relationships, we gain insight into the integration risk of the function.

The next two sections translate these principles into a set of rules and a systematic procedure for capturing chains. The chain capture procedure amounts to documentation of the correct relationships in and between the physical elements that affect the final position of a set of features on different parts that carry function. The contribution here is a consistent procedure that preserves the established principles, can be used when little about the design is defined, supports analysis of many chains, and guides a qualitative comparison process that leads to quantitative analysis during concept design. While the physical principle of chaining physical dimensions is not applicable to all domains, it has broad and direct application to electro-optical-mechanical products where dimensional relationships affect function in many domains.

The reader can proceed in two different sequences. One is to read through Chapter 4 fully, then the more extensive examples in Chapter 5. Chapter 4 mixes a few simple and complex examples into the discussion so the reader can proceed directly. An alternative is to read Sections 4.1 through 4.3, then proceed to the examples and assess the chains specific to one or more of the examples of Chapter 5. If the latter approach is taken, the matrix representation in Section 4.4 will be skipped. The reader can return to this chapter at a later time to review the matrix representation, discussion of quantitative variation analysis, and documentation of the architecture.

4.1 Chain Definition and Principles of the Chain Capture Procedure

This section presents the mechanical domain approach to solving the problem of interest: which elements chain together to deliver some end dimension of interest - which I call a *Product Key Characteristic* (PKC) - that in turn delivers some important product function? This section describes the principles that serve as the basis for a chain capture procedure applicable in concept design along with a set of rules for representing chains graphically. The principles rely on the same basis as quantitative assembly modeling, as described in Section 3.3.3, but cannot rely on the level of detail or completeness that a quantitative analysis uses because such detail is not available during concept design. Chains are defined first and two examples are introduced. Information that can be reasonably expected to be available during concept design is then reviewed, from which constraining assumptions on any feasible chain capture procedure are derived. Principles are then described that transfer the essence of the quantitative approach to the limitations of concept design. A procedure that can operate within these constraints is then described, followed by two examples, and then rules for representing the chains graphically. I then formally define a set of KC terms that will be used in the remainder of the thesis.

4.1.1 Chain Definition and Introduction to the Graphical Representation

The type of functions we are interested in are those delivered by the relative positions of features in different elements of the physical hierarchy. I use the name *end features* for the two or more features whose relative location is the PKC. To establish the terminology I use the simple, unmodified name "chain" for:

> **a graphical representation of dimensional relationships that affect the final relative positions of the end features (the PKC) of interest, depicted on a hierarchy of the physical elements, where each dimensional relationship can lie within a single element (parts, components, sub-assemblies, etc.) or between elements.**

Figure 4-2 shows examples of the graphical representation that are explained in depth below. [1] Figure 4-2a shows the C-17 nacelle inlet skin to engine bay door alignment PKC chain. The chain indicates that the PKC is delivered by dimensions in four elements (the red arrows) and three interactions between elements (the blue arrows). Figure 4-2b shows the chain for one PKC associated with the alignment of keels in one of the decompositions of the JSF. These examples will be explored in more depth in the discussion that follows.

[1] Both are discussed in Chapters 1 and 3.

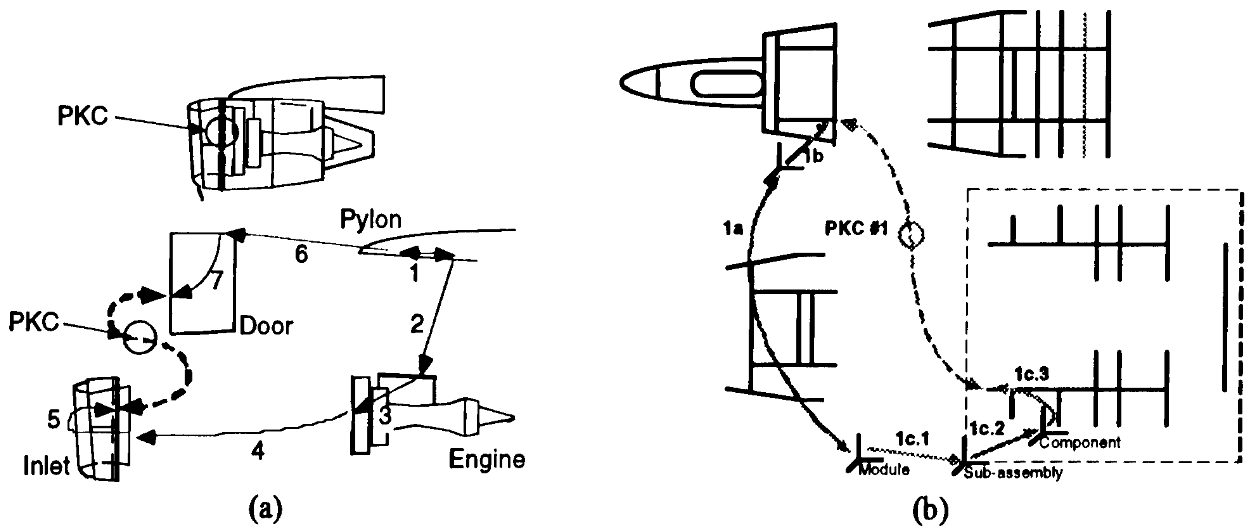

Figure 4-2. Examples of the graphical chain representation.

Let us review the definition of chain in the context of the images in Figure 4-2. The chain is a graph. The arcs in the graph (called the *links*) are dimensional relationships and can be depicted either with double or single-headed arrows, with the rules defined below. The graph is depicted on icons representing the physical elements of the WBS to directly relate each dimensional relationship to the element or interaction among elements that contains the dimensional relationship. The links are numbered to correlate the graphical representation to information contained in a linked list that describes each link, which is described in more detail in Section 4.2.6.

4.1.2 Information in Chains

The following develops constraints for a concept design chain capture procedure based on the information needed to capture quantitative chains versus information that is reasonably expected to be available during concept. The ideas are illustrated in the context of the C-17 Nacelle example. Two definitions are required for the discussion:

- *end feature*: name for the features whose relative location is a PKC
- *reference frame*: the set of features in a physical element used to locate the element relative to other elements.

4.1.2.1 Limited Information in Concept Design

A quantitative chain is described by two main types of information: a decomposition all the way down to individual parts, and knowledge about how the parts are connected to each other (by what are called assembly features) to form the assembly. From this information one can construct a quantitative model of how the PKC is achieved, including a variation analysis.

In concept design, the decomposition is incomplete because there usually is no time for a complete decomposition down to the last part and because such detail is not necessary for most concept design evaluations. If we require the chain procedure to have such detail, the procedure will not be used. The situation in Figure 4-3 is typical, where the physical hierarchy is incomplete. The absence of detail is in fact an advantage that should not be sacrificed needlessly.

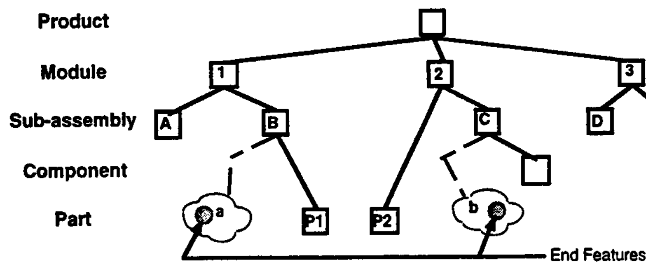

Figure 4-3. Illustration of a WBS where decomposition is incomplete, as befits a concept design. Some portions are known down to the level of single parts while others end in undifferentiated subassemblies. Also shown are two end features buried in undefined components, which must be related accurately in space in order for a PKC to be delivered.

The absence of detail frees the designers to undo and revise their designs and delays commitment until it is necessary. Therefore the chain method must be able to deal with incomplete decompositions.

An incomplete decomposition lacks information about assembly features. Therefore we do not know the reference frames for individual parts and cannot duplicate the detailed locational information that is found in a quantitative assembly model. Therefore the chain method must also be able to deal with incomplete knowledge of the reference frames.

At the same time, the method needs to obtain and preserve as much of the quantitative assembly information as possible. It will therefore seek to exploit any connective definitions available and encourage the designers to develop such information.

4.1.2.2 Necessary Information for the Chain Capture Procedure

We require a chain that captures relationships between elements down to some predetermined level in the decomposition hierarchy that allows us to document the elements involved in achieving a dimensional relationship between two or more end features. For example, in Figure 4-3, we require a chain complete down to the level of subassemblies that shows how the PKC between end features 'a' and 'b' is achieved. We assume that the designer can recognize which of the defined elements contain the end features 'a' and 'b'. We do not require that the designer know the parts that contain the end features, which are depicted by the clouds in Figure 4-3 to represent that they have not been identified at this stage of the decomposition process.

We recognize that three reference frame relationships are needed:

- from module 1 to module 2, each of which contains one end feature
- from module 1 to sub-assembly B, which contains end feature 'a'
- from module 2 to sub-assembly C, which contains end feature 'b'.

We do not need to know what the parts are, what part or higher level assembly features will be used as the reference frames, or any of the geometry to recognize the structure of the chain that can be used during concept design. Now, we require a procedure to capture the chains systematically. The principles described in below make only two assumptions:

1. Decomposition candidates are available down to the level of interest; e.g. if we require understanding of how the KCs are mapped to sub-assemblies, each candidate decomposition includes the level of individual sub-assemblies (but not necessarily the levels below).
2. We know which elements in the hierarchy of a candidate decomposition contain one or more end features; e.g. which modules and sub-assemblies contain the end features in Figure 4-3.

Figure 4-4a shows the incomplete decomposition of the C-17 nacelle and the example PKC. Figure 4-4b shows the end features. One end feature is the aft edge of the inlet skin. The other end feature is the forward edge of the door. In this example, we know the reference frames that accompany this incomplete decomposition.[2] At the level of the nacelle assembly, the reference frame for the inlet/engine sub-assembly is in the engine lugs, and the reference frame for the door is in its pylon hinge (see Figure 4-4c). Note that these two reference frames are carried in the pylon at the features that mate the pylon to the engine and door. In the sub-assembly of the inlet

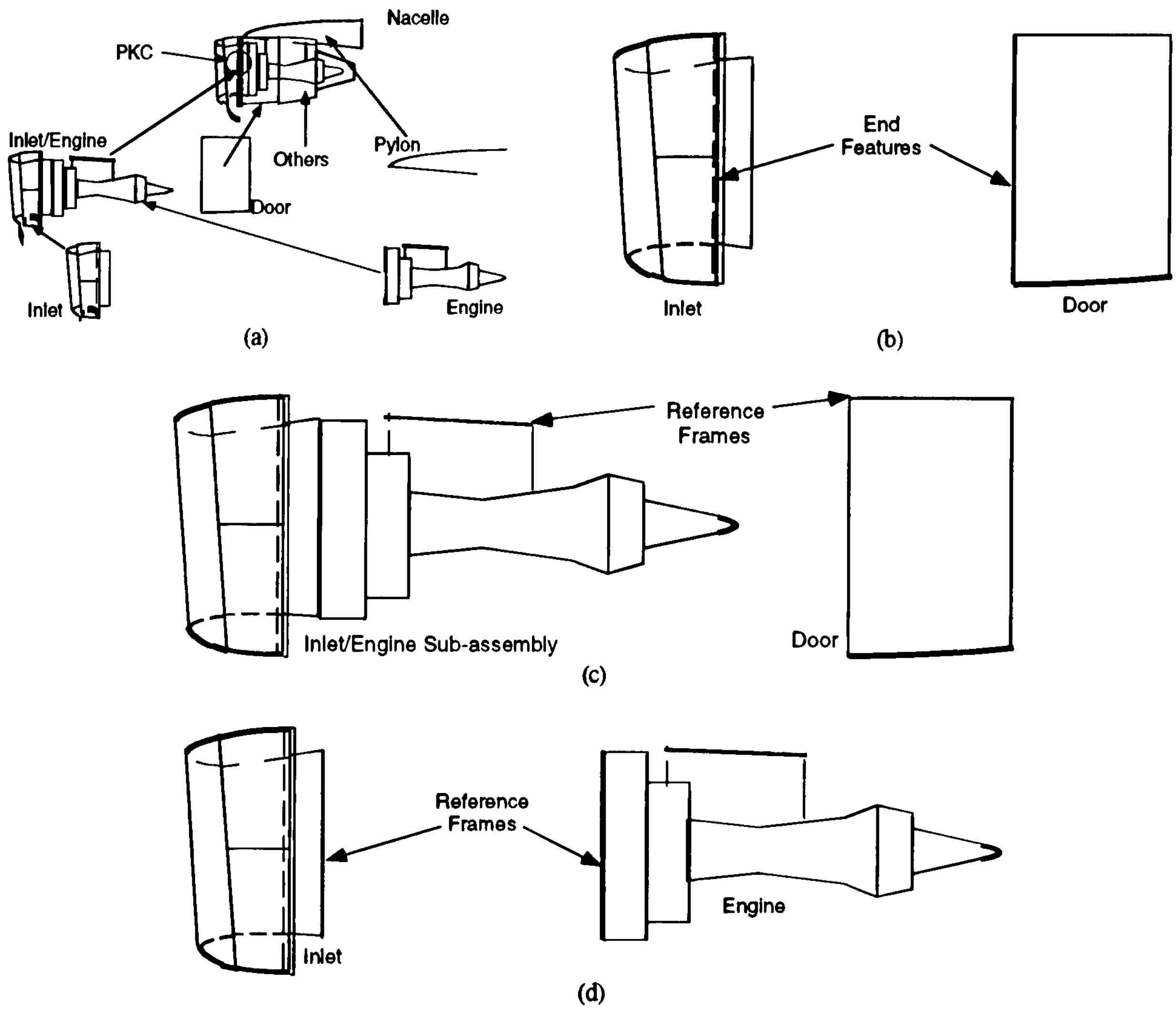

Figure 4-4. C-17 nacelle example PKC: (a) decomposition, (b) the two end features, and reference frames (c) at nacelle assembly and (d) at inlet/engine sub-assembly.

[2] The JSF keel alignment PKC introduced in Figure 4-2b will show a case where the reference frames are not known.

to the engine, the reference frame for the inlet is its surface that mates to the engine, and the reference frame in the engine is its surface that mates to the inlet (see Figure 4-4d).[3]

4.1.3 Principles of Chains

The physical basis of chains is that a physical element is located in space by some reference frame in that element, and that dimensional relationships among the reference frames at several levels of the decomposition hierarchy and the end features determine how the end features are located relative to each other. I state five principles that generalize the physical basis of chains:

1. **Every physical element has a reference frame.**
2. **The PKC is *delivered* in the lowest element in the decomposition hierarchy that has acquired (by fabrication and/or assembly) all the end features and is stable, so that the relative location of the end features remains intact through all subsequent levels of assembly. This lowest element is called the *root element.***
   Stability rule: The root element is stable if it is not compliant in degrees of freedom (DOFs) that are defined in the PKC.
3. **In documenting chains we leave the reference frame for each element denoted as "unassigned", i.e. no sub-element(s) is designated as that which contains the reference frame. In this way we do not make any assumptions about which parts or features are used as the reference frame.**
   Uniqueness rule: There can only be one reference frame for an element in each step in the assembly process.[4]
   Consistency rule: When an element's reference frame is assigned, it must be assigned the same for all chains that include that reference frame.
4. **A chain's *span* is established at the point at which the PKC is delivered. Span is defined in Section 4.3.1.**
5. **Chains have a two part structure:**
   - **Chains initiate at a *root link* that defines the dimensional relationship between the elements containing end features that are assembled in the root element. The root link is discussed further below.**
   - **Chains contain *branches* that 1) initiate at the root, and 2) include links of dimensional relationships that extend down from the root link to the end features, passing through various elements at the different levels of the hierarchy and implying dimensional relationships between them.**

Each principle makes a specific point that allows us to create a chain capture procedure relevant to the information that is available in concept design. Principle #1 indicates that it does not matter if we do not know the exact assembly features that make up the reference frame of an element. Regardless of whether the specific features have been defined and assigned to serve as the reference frame, there still must be a reference frame for every element. We say that the reference frame is "unassigned" but proceed knowing that one will be defined eventually. Principle #2 states the only elements that affect a PKC are sub-elements of the root element. Principle #3 states that the procedure does not require that any decisions be made about reference frames; its rules guide us through how to apply any specific reference frame decisions that can be made. By capturing the chains with unassigned reference frames, different reference frame options can be investigated. Principle #4 states a character of chains called "span" that will be utilized in the metrics. Principle #5 indicates the structure of chains.

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[3] In reality these are rings, one in each component, that have matching hole patterns for attach bolts.

[4] For example, if an element is located for assembly to another element, there is only one reference frame. If a third element is brought in, the same reference frame can be used or another can be selected. If all three are assembled in one step, there can only be one reference frame.

4.1.4 Procedure for Two End Feature PKCs

The five principles guide a chain capture procedure. The following procedure is applicable to PKCs involving two end features, which is by far the most common type that I have encountered to date. PKCs with more than two end features are also possible, and the an informal description of the procedure for these cases is discussed in Section 4.2.2. The two end feature procedure is:

1. **Identify the root element.**
2. **Document the "root link" in the chain: this is the link between the two elements, each of which contain one end feature, that are mated in the root element; I have identified two cases:**
   a) **the root link is the dimensional relationship between the *reference frames* of the two elements; this relationship is either delivered in a fixture or is a direct mate between features of the two elements.**
   b) **the root link is a dimensional relationship in a *third element* to which the two elements containing an end feature are assembled.**
3. **Document each of the two "branches" of the chain from the end of the root link to the end feature. Each branch systematically captures the relationships between reference frames in each level of the hierarchy. The final link in each branch runs from the lowest element defined that contains an end feature to the end feature.[5]**
4. **Apply any knowledge about specific reference frame assignment, or options that may be considered (this step interacts with the two cases in step 2).**

4.1.4.1 Simple Two End Feature Example

For the example in Figure 4-3, a chain can be captured just with the reference frame relationships listed in Section 4.1.2.2. Step 1 in the procedure involves recognizing that the final product is the root element because this is the lowest element in the hierarchy that contains all the end features. Step 2 involves documenting the root link between the two modules that contain end features, since each module contains one end feature and they are the two elements fully constrained relative to each other in the root element. Figure 4-5 shows two cases that match those discussed above. Figure 4-5a shows the root link if the dimensional relationship is between the reference frames of the two modules, and shows dashed lines that represent the branches of the chain that run down the through the modules (to be captured in the next step). Figure 4-5b shows the root link in module 3 if modules 1 and 2 are assembled to module 3, and dashed lines that represent the branches running *to* and *then* down through the modules. In practice, options that match either of the two cases may be investigated, or one option may be recognized as preferable for the candidate decomposition. Step 3 involves capturing a branch in each module. In the example, there are two links in each branch: one from the module reference frame to the reference frame of the sub-assembly that contains the end feature, and a second from the sub-assembly reference frame to the end feature. Figure 4-6 illustrates these relationships in a graphical chain for the root link case of Figure 4-5a. Five dimensional relationships make up the chain:

1. between the two modules (the root link)
2. between the module 1 reference frame and the sub-assembly B reference frame[6]
3. between the sub-assembly B reference frame and end feature 1
4. between the module 2 reference frame and the sub-assembly C reference frame
5. between the sub-assembly C reference frame and the end feature 2

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[5] More detailed discussion of this step is in Section 4.2.2 and Appendix C.

[6] Again in keeping with Principle #3, we do not assume that the module and sub-assembly reference frames are the same. If they are eventually assigned to the same features, then the two reference frames will be the same and this link will disappear. This is a downstream decision that will affect many PKCs in a real product.

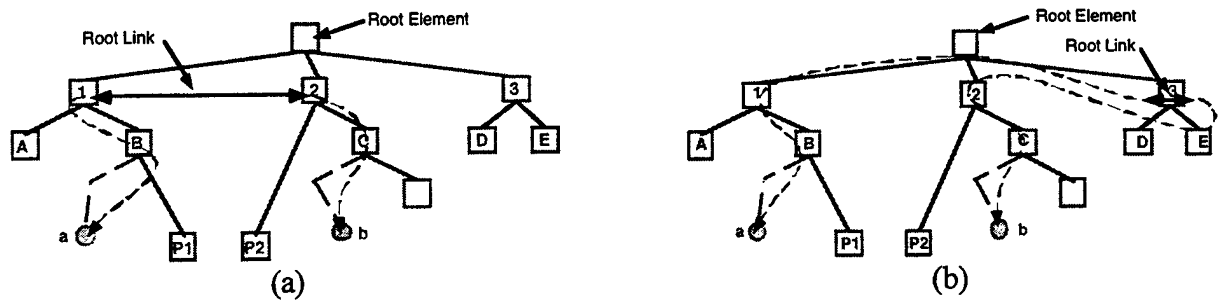


Figure 4-5. Two cases of the root link for the example in Figure 4-3, (a) between the reference frames of the two modules that contain an end feature, and (b) in a third element to which the other two modules are assembled.

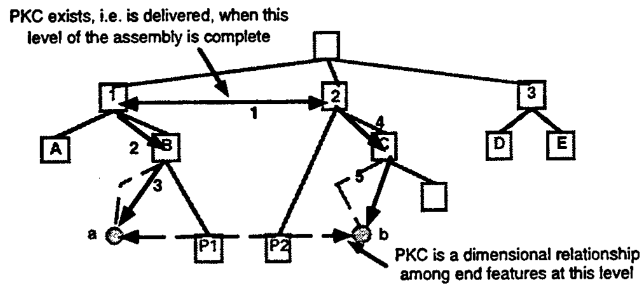


Figure 4-6. A chain representing the five dimensional relationships that deliver the PKC.

Note that Figure 4-6 clarifies two important aspects of KC delivery. A PKC is denoted as a relationship between a set of features at the level of parts. But, the PKC is not delivered, i.e. it does not exist in the assembled product, until all the links are achieved, including those at higher levels in the hierarchy that correspond to downstream steps in the assembly process. The chain depicts each physical element that plays a role in achieving the PKC.

4.1.4.2 Reference Frame Decisions

While the first three steps in the above procedure create the basic structure of the chain, step 4 involves adding additional information regarding the reference frames that increases the level of detail in one or more branches of the chain. For an existing assembly, like the C-17 nacelle, the reference frames for a physical element are defined all the way to specific assembly features. As stated above, this information is not available for capturing a chain during concept design. We can break the decisions involved in defining a reference frame into four stages involving increasingly detailed definition:

- proximity: the region of an element where a reference frame is to be
- assignment: the exact sub-element in which a reference frame is to be
- datums: the portions of individual parts that are to be reference locations
- features: exact features that are to be used in assembling the parts.

Based on our assumptions about concept design, the latter two stages will not be achieved.[7] However, a team may be able to achieve the first two stages because they do not require decomposition to be complete to the level of parts, nor do they require explicit decisions about the reference frames just for the sake of a more accurate chain analysis. Appendix C discusses

[7] As defined by Adams [1998], a system for choosing datums and specific assembly features has been developed.

how reference frame information can be used in the procedure, and the examples in Chapter 5 and case study in Chapter 7 discuss how reference frame options can be used in capturing chains.

4.1.5 Examples of the Two End Feature Chain Capture Procedure

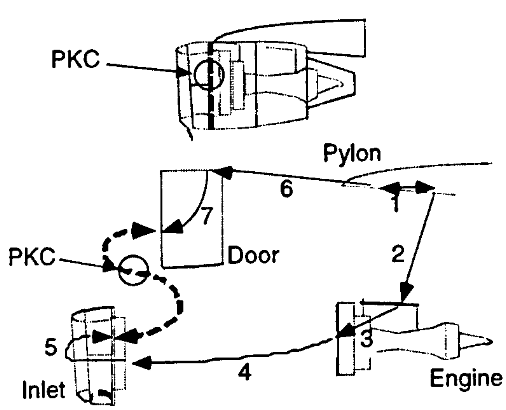
4.1.5.1 C-17 Nacelle Example PKC

In the C-17 nacelle example, the chain in Figure 4-7a, with the links listed in Figure 4-7b, is derived by applying the principles and the procedure. Principle #1 was demonstrated in Figure 4-4c and 4-4d where the reference frames were listed. Principle #2 is demonstrated by the fact that once the full set of end features (the two surfaces) are fully constrained, assuming the assembly is stable (which it is), the PKC is delivered. This occurs in the nacelle, the root element. Principle #3 is not followed because the decomposition and mates are already fully defined, but the rules that follow this principle must be followed. Also note that the reference frames for the inlet/engine sub-assembly and the engine both are assigned to features in the engine, but that these reference frames are assigned to *different* features.

The procedure is followed to capture the chain. The root link is the relationship between the inlet/engine sub-assembly, and the door, the two elements joined in the root element that contain the end features. Here, case (b) for step 2 is invoked because these two elements are mated to a third element, the pylon. Link #1 lies in the pylon: it is the dimension from the door attach point to the engine attach points, and is the root link for this chain. There are two branches in the chain that run from the root link to the end feature in the branch:

- links 2-5 in the inlet/engine branch: the mate of the engine to the pylon, in the engine from its lugs to the inlet attach ring in the engine (a relationship between the two reference frames assigned to the engine), the mate of the inlet to the engine (from reference frame to reference frame), and in the inlet from its reference frame to the end feature
- links 6-7 in the door branch: the mate of the door to the pylon, and in the door from its reference frame to the end feature.

The Consistency rule is illustrated by introducing the chain for a second characteristic: the gap between the aft surface of the inlet and forward surface of the engine. These surfaces are the



(a)

Link	Description
1	Relative position of the engine and door attach points
2	Attachment of engine lugs to pylon
3	Relative position of inlet attach ring in engine and engine lugs
4	Attachment of inlet to engine
5	Relative position of skin edge to engine attach ring in inlet
6	Attachment of door to pylon
7	Relative position of forward door edge to hinges in door

(b)

Figure 4-7. C-17 example PKC chain.

reference frames shown in Figure 4-4d, now they are end features for this second characteristic. Using the existing reference frames described in Figure 4-4, this chain is simple; it is fully established in the inlet/engine sub-assembly, and is established in the mating of the inlet to the engine directly (link 4 in the PKC chain in Figure 4-7a). Say we would prefer to use the end feature in the inlet for the PKC as the reference frame when the inlet is attached to the engine. Both chains change. Figure 4-8a shows the new PKC chain. This chain is now simpler than that depicted in Figure 4-7a because the relationship between the inlet/engine reference frame and the end feature is established in one link instead of in three. However, the chain for the second characteristic is now more complex, involving three links instead of one.

This example shows how two chains can conflict. The Reference Frame Principle states that we can choose only one reference frame for each element. The reference frames must be applied consistently in order for the chains to be captured accurately. Ideally, we would prefer to achieve the simple chains for both the PKC and second characteristic if we were not limited to one reference frame choice. In reality this limitations exists. In the actual C-17 process, the inlet reference frame used in assembly to the engine was chosen to be the surface that attaches to the engine directly because any inlet must attach to any engine for maintenance and support considerations. If the PKC end feature had been chosen, the chain is altered so that delivery of the second characteristic is now in question. Any resulting gap between the engine and inlet would have to be corrected in some way, say with shims, and all inlet/engine mates would be unique. This would perhaps make the inlets not interchangeable. By choosing to make the inlets interchangeable, we make the chain for the PKC more complex.

4.1.5.2 JSF Keel Alignment PKC

The same principles are applied to capture the chain showing the alignment of the keel in the JSF decomposition 'I'.[8] Figure 4-9 shows the decomposition of the airframe into four modules, of the bay module into two sub-assemblies, and of one of the sub-assemblies into three

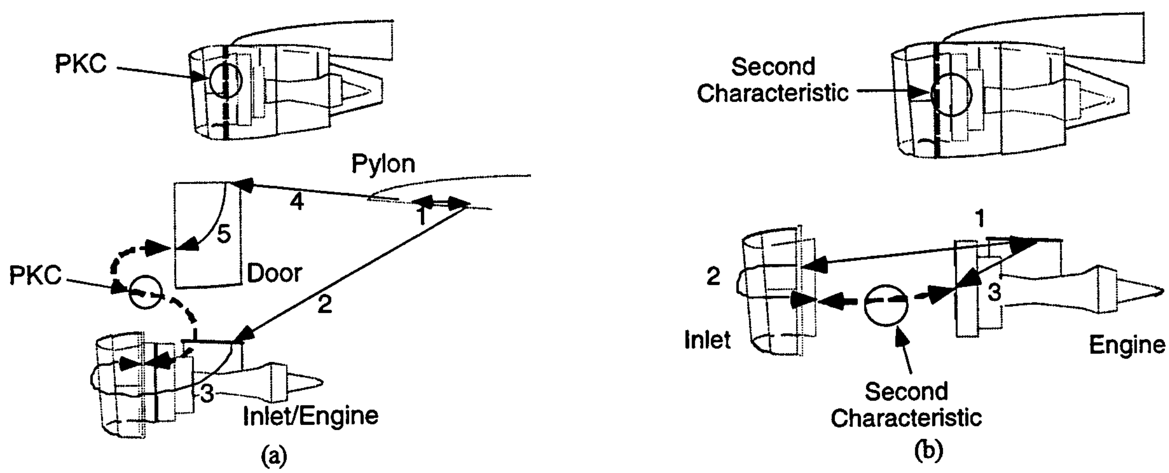


Figure 4-8. C-17 (a) example PKC chain and (b) chain for second characteristic, when reference frame for inlet used at inlet/engine sub-assembly is chosen as the PKC end feature (inlet skin edge).

[8] Note that this is one of four PKCs in this example. In Chapter 7, I refer to this type of PKC that spans modules as a "Module KC."

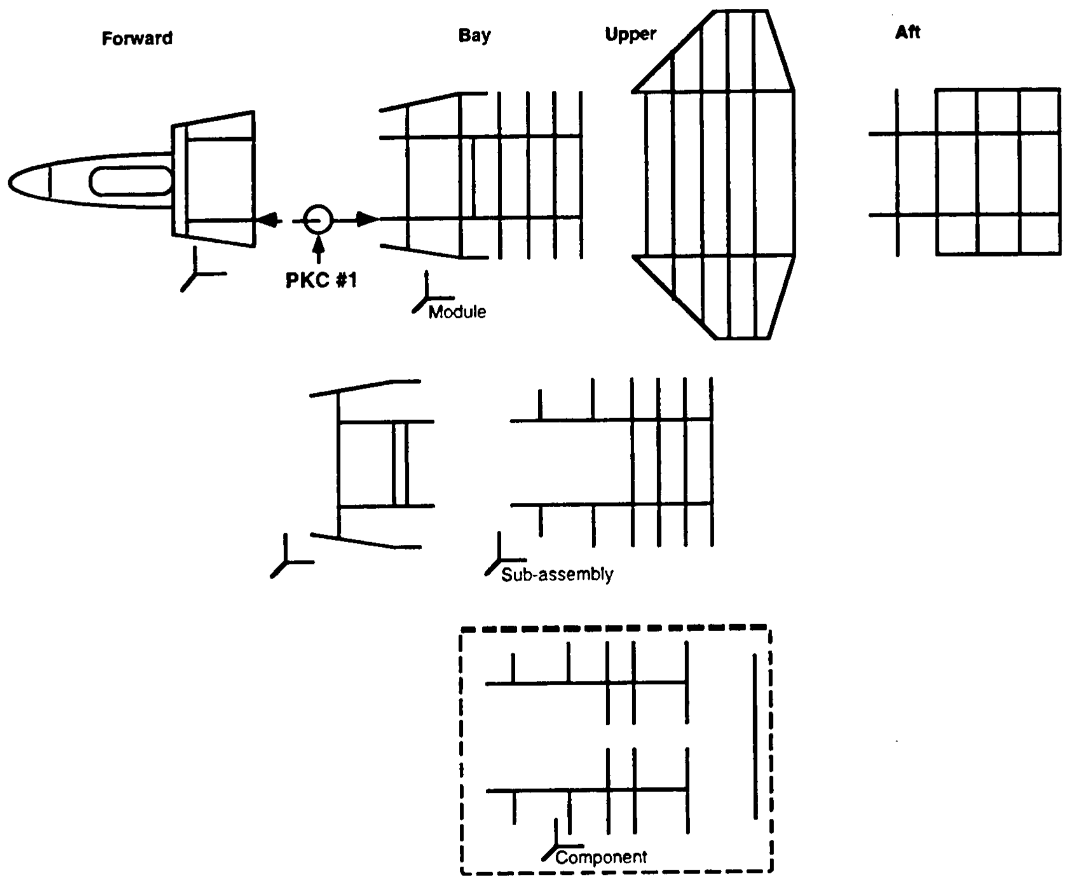


Figure 4-9. JSF decomposition 'I' with the PKC shown.

components. The end features are the two edges of two keels[9] that must align. In this example none of the reference frames are assigned, but a generic reference frame is depicted for each module, sub-assembly, and the component containing the end feature in the bay module.

The PKC is delivered in the mate of the forward and bay modules, so the airframe is the root element. This is an example of case (a) in step 2 of the chain capture principle, where the root link is a relationship between the reference frames of the two elements containing the end features. In this case let us capture the chain in two stages: first at the level of the modules, and second within the bay module. Figure 4-10a shows the root link and one link in each module from its reference frame to its end feature. Figure 4-10b shows one branch of the chain, the portion in the bay module, that is a more complete description of link #1c. The links are numbered by adding a digit after the 1c. The four links are:

1. relative position of the module reference frame to the sub-assembly reference frame
2. relative position of the sub-assembly reference frame to the component reference frame
3. relative position of the component reference frame to the end feature.

The combination of the two chains is shown in Figure 4-2b.

[9] Recall that in this example the design is in the concept phase. These keels are not distinguishable parts nor are defined in any detail.

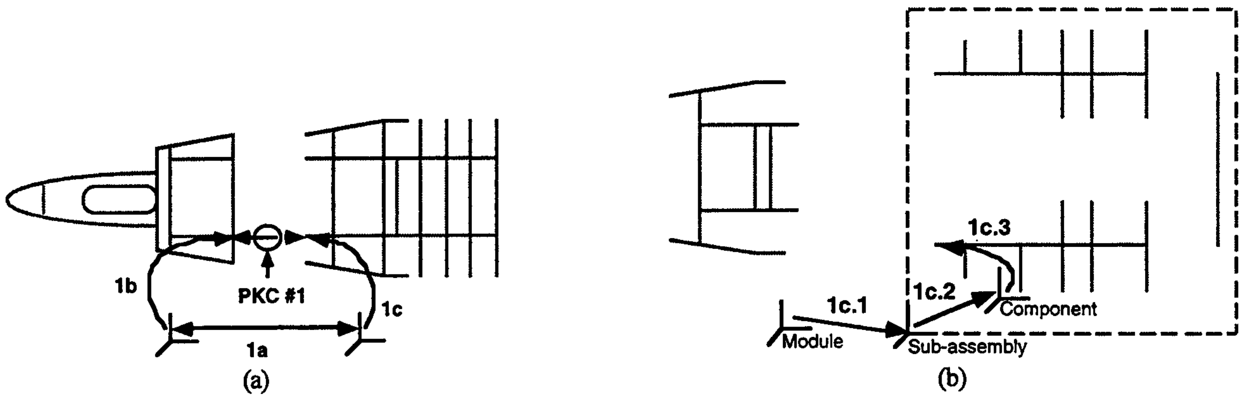


Figure 4-10. For the JSF keel alignment PKC: (a) the chain at the level of the root element, and (b) the branch in the bay module.

By capturing the chain with the generic reference frames, the IPT is in a position to explore options for reference frame assignment. Two possible options are shown in Figure 4-11. Figure 4-11a shows chain if the bay module reference frame is assigned to the sub-assembly that does not contain the end feature. Figure 4-11b shows the chain that results if the bay module reference frame is assigned to the component containing the end feature. The chain in Figure 4-11b is simpler than the one in Figure 4-10b. The ability to simplify a chain in this way is captured in the definition of "height" described in Section 4.3.1. Because many chains are present in this module and different chains will be simplified in each option, these options must be explored consistently for each chain affected by the reference frame assignments.

4.1.6 Graphical Representation

The power of the chain is in its ability to graphically communicate what relationships in and between what elements are critical to delivery of a PKC. The following states rules for graphical chain representations.

4.1.6.1 Link Display

There are three rules for representation of the chain links, as illustrated in the examples above.

Root Link Representation: a root link is represented as a double headed arrow
PKC Representation: the PKC is represented as a double-headed arrow

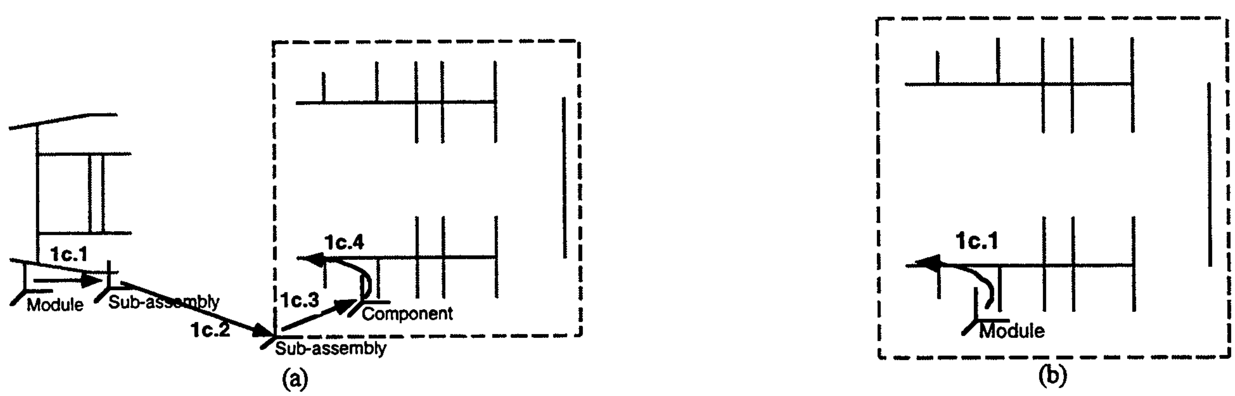


Figure 4-11. For the JSF keel alignment PKC: the chain if the bay module reference frame is assigned to (a) the sub-assembly that does not contain the end feature, or (b) the component that does contain the end feature.

Branch Link Representation: all links in each branch are depicted as arrows that point away from the root link and toward the PKC.

4.1.6.2 Two Hierarchical Displays

There are two forms of display on hierarchies of the physical elements. The first, called Schematic Display, is to depict the chain links on sketches of the physical elements, as illustrated in the two examples in Section 4.1.5. This form is useful because it provides visual recognition of the physical elements for the viewer. Selected physical elements can be displayed, as I chose to do in the two examples in Figure 4-11. Three dimensional schematics are especially powerful, as would be used in practice with a solid modeling CAD package. One rule for this display is:

Schematic Display Rule: if case (b) of step 2 in the chain procedure applies, the element containing the root link must be displayed.

An alternative is depict chains on the physical hierarchy, called Hierarchy Display. This form is useful because it emphasizes how chains show interconnections between elements that fall outside the assembly tree, and organizational hierarchy that typically accompanies the physical hierarchy. The simple example in Figure 4-6 shows a chain depicted on a physical hierarchy, and this form is used in several examples in Chapter 5. There is a choice involving which links to display, all or just those indicating interconnections. A rule for this is:

Hierarchy Display Rule 1: at a minimum, interactions between elements should be displayed; display of links within elements is optional.

A second rule guides how to display a chain when reference frames are assigned. If all links were shown between the elements that contain the reference frames, then the figure would be crowded by a number of lines at the bottom between the individual components. The Hierarchy Display is clarified when the links are drawn at the level in the hierarchy at which the reference frame is used; e.g. if a link involving the module reference frame is to be shown, the link should be drawn to the module level of the hierarchy instead of to the element to which that reference frame is assigned. The exception is that, if the reference frame is assigned to the element containing the end feature in that branch, then the link is drawn to that element at the lowest level. This exception visually emphasizes how a chain is simplified depending on reference frame assignment, like that in Figure 4-11b.

Hierarchy Display Rule 2: links are drawn at the level in the hierarchy at which the reference frame is used, except in the case where the reference frame is assigned to the element that contains the end feature, at which point the link is drawn directly to the element at its lowest level.

The Hierarchy Display for the examples in Figure 4-11 are shown in Figure 4-12. In figure 12, the sketches from the previous displays are arranged hierarchically.. In the case where the reference frame is assigned to the bay sub-assembly that does not have an end feature (Figure 4-11a), the root link is drawn to the module level, as shown in Figure 4-12a. An optional link can be shown from the module to the sub-assembly to which the module reference frame is assigned. Links in the branch containing the end feature are shown. Figure 4-12b shows the case when the reference frame is assigned to the element containing the end feature, where the root link is drawn

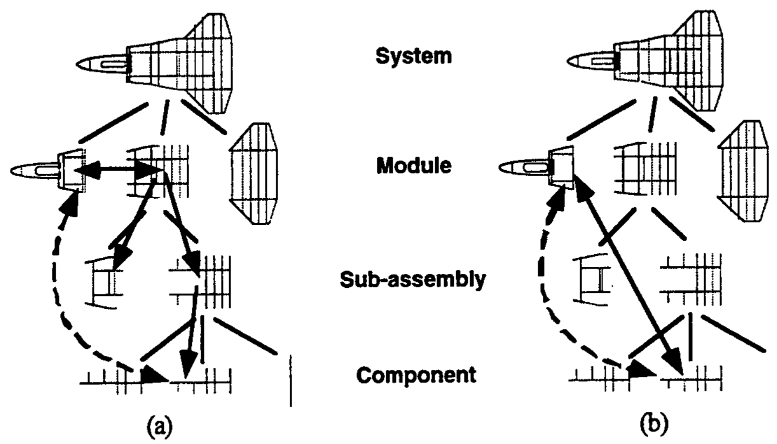


Figure 4-12. For the JSF keel alignment PKC: the Hierarchy Display if the bay module reference frame is assigned to (a) the sub-assembly that does not contain the end feature, or (b) the component that does contain the end feature.

directly to the element containing the end feature. Recall that Figure 4-6 shows a third example, a chain depicted on a hierarchy when the reference frames are unassigned.

4.1.7 Key Characteristics

Following the tenets of EQFD [Clausing 1994], the IPT should apply chain analysis to the "critical few" requirements that are likely to most affect customer satisfaction with the product. Recall that Ulrich and Ellison [1997] found that, even in many simple products, of the few functions that differentiate a product and affect customer satisfaction, many are "holistic" (i.e. integral) and therefore are candidates for analysis that chains can support. Section 3.2.2.1.2 introduced the industry approach to KCs that is in line with this thinking.

4.1.7.1 KC Definitions

In prior work my colleagues and I introduced a set of definitions for *Product Key Characteristics* and *Assembly Key Characteristics* [Cunningham et al]. The following list updates these definitions and adds terminology needed to simplify the chain description below[10]:

- Key Performance Parameters (KPPs): the subset of the product's performance requirements on which a concept design is found to have marginal performance, and hence the product is highly sensitive to any performance degradation due to variation from nominal. KPPs are concept specific.
- Key Characteristics (KCs): the subset of the concept's geometric characteristics and material properties that are highly constrained or for which minute variations from nominal specifications (regardless of manufacturing capability) have a significant impact on the customer's satisfaction with the product's KPPs, cost, or delivery schedule.[11] KCs are concept specific but decomposition independent.
- Product Key Characteristic (PKC): the relative location of features whose variation from nominal will adversely affect the KC; PKCs are captured at each level of the product

[10] There is no standard set of terminology, though research seeks to establish a single set of terms [CIPD].
[11] Two other definitions are "External KCs" (those that affect customer perception of quality) and "Internal KCs" (those that affect the company's ability to deliver the quality for the expected cost or delivery schedule).

decomposition, where they often are found to be relationships between features of different parts. Some PKCs are decomposition dependent.[12]

- Assembly KC (AKC): the relative locations of features on different parts during each assembly stage on the product, tool, or fixture, that affect one or more PKCs.
- Part KC: the relative locations of features on the same part that affect a PKC.

4.1.7.2 KC Rules

There are two rules that result from these definitions:

PKC Rule: a chain is captured for each PKC.
AKC/Part KC Rule: every link in a chain is either an AKC or Part KC; each can be expanded as a portion of a branch of the chain.

4.1.7.3 KC Terminology Hierarchy

Figure 4-13 shows the hierarchy that accompanies this terminology. All concepts must satisfy a set of cost and performance requirements derived from customer needs. Each concept has its own set of KPPs, though repetition of KPPs among the concepts is certainly possible or even likely for particularly challenging requirements. Each concept also has a set of KCs that deliver the KPPs. These are independent of decomposition. Each KC spawns one or more PKCs, some of which are decomposition independent and others that are decomposition specific.[13] Section 4.4 shows how metrics are applied to the chains in the context of this hierarchy.

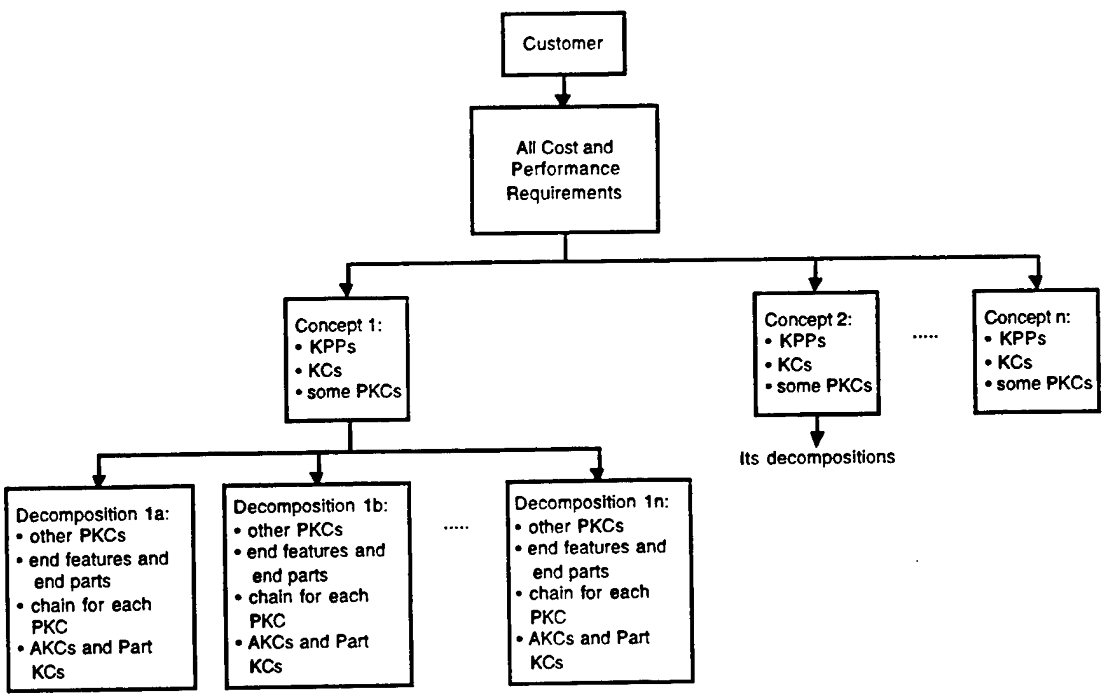


Figure 4-13. A hierarchy of KC terminology related to candidate concepts and decompositions.

[12] Section 6.1 discusses the identification of KCs and PKCs.

[13] In the detailed case study in Chapter 7 we gave these different types of PKCs different names. We created one name for the PKCs that are decomposition independent, another for the set that exists for the families of decompositions (that have the same modules), and a third for the set that is truly specific to each decomposition.

4.2 Chain Properties

This section demonstrates six properties of the chain representation that make it a tool appropriate for addressing the shortfalls of existing functional-physical mapping methods, to the conditions of concept design, and for the coordination of the IPT. Chains exhibit the following:

- they allow the IPT to make qualitative evaluation of function delivery despite the limited information available during concept design
- are generated via a systematic procedure
- distinguish the functional-physical mapping of different physical décompositions
- indicate coupled and conflicting issues related to function delivery
- establish the building blocks for formal assembly modeling analysis
- relate function delivery to the elements of the WBS and technical and non-technical attributes of those elements

4.2.1 Chains Enable the IPT to Evaluate Function Delivery During Concept Design

The first property is the most critical: with chains, the IPT is able to depict function delivery and analyze the associated integration risk, and do so despite the limited definition of the candidate concepts during concept design. The team is now able to qualitatively assess the integration issues early in design *when the opportunity to control the outcome is greatest.* Chains accomplish this by retaining the scientific basis of tolerance chains, but elevating the focus to the level of dimensional relationships in assemblies. Integration issues are revealed in the recognition of the assembly-level dimensional relationships that impact functions. Other methods fail because they rely on recognition of part to part relationships, which are not available in concept design and therefore disqualify methods that rely on such information.

4.2.2 Chains are Generated Via a Systematic Procedure

The second property is that chains are generated via a systematic procedure. Section 4.1.4 described a simple procedure for two end feature PKCs. The following explains the general procedure informally.

Assuming the minimum information about the incomplete decomposition and elements containing the end features is available, chains are captured in a procedure that documents all the links in and between elements containing less than the full set of end features. The general procedure simply contains more possibilities than in the two end feature case, as noted in steps 2 and 3:

1. **Identify the root element and all elements containing sub-sets of the end features.**
2. **Document the root link(s) among two or more elements that are mated into the root element; the same two cases apply as in the two end feature case.**
3. **Document each branch of the chain from the end of the root link to the end feature. Each branch systematically captures the relationships between reference frames in each level of the hierarchy. When there are more than two end features in a branch and they lie in different elements in the branch, the branch itself branches off further.**
4. **Apply any knowledge about specific reference frame assignment, or options that may be considered.**

Appendix D describes the procedure formally, discussing patterns in the more than two end feature cases and outlining an algorithmic approach to capturing chains.

4.2.3 Distinguishing Functional-Physical Mapping of Different Decompositions

The third property is that chains indicate the different integration issues in the functional-physical mapping of each candidate decomposition. As the chain capture procedure description indicates, the reference frames that are relevant in the alignment of a set of end features are determined at the same time as the physical decomposition. The relevant reference frames will differ for each decomposition because each decomposition defines different elements. And, some or all of the end features of a PKC will end up in different elements. Because the chain is simply a map of relationships among the relevant reference frames of different elements, the basic structure of chains is a product of the decomposition, where different elements are likely to interact in the delivery of each characteristic. The examples in Chapter 5 and the case study in Chapter 7 illustrate this point.

4.2.4 Ability to Identify Coupled and Conflicting Chains

In a product complex enough to be of interest, we deal with many chains, some of which will indicate that delivery of different functions is in fact coupled. Coupled functions have the characteristic that one physical relationship may alter the delivery of a set of functions. In the context of chains, I use the term "coupled" to refer to *chains that share the same interactions between elements*. Coupling is represented in the results of the procedure because it captures reference frame relationships both in and between elements. Coupling is depicted in chains that have common links between elements.

Coupling in itself is an indicator of complexity. Conflict is a type of coupling that represents significant complexity. Conflicting chains occur when insufficient DOFs are available to independently control the position of each end feature. This occurs when two or more end dimensions share the same interaction between elements and require alignment in the same DOF(s). If the DOFs relevant to each PKC are fully defined and the proper datums have been identified, then conflicts can be identified very early in chain definition. Even if information to identify conflicts is not available, coupling is readily apparent when the decomposition occurs. It is important at a minimum to identify the coupling to properly evaluate the architecture. The graphical chains are an early indicator of coupling before quantitative information can be applied.

The JSF case illustrates this point. Let us review the coupling of the keel alignment PKC and "weapon bay hinge line PKC" discussed in Section 3.2.4. The chains cross the same module break in decomposition family 1. Both chains include the same interaction among the modules, so the PKCs are coupled. In module 3, the dimensions from the module reference frame (which may be unassigned) to both the keels and the weapon bay hinge line attachments are each involved in the delivery of a PKC. In this case we can also foresee conflict. Keel alignments are most critical in the buttline direction.[14] Weapon bay hinge lines are critical in both the buttline and waterline directions. The buttline DOF can not be achieved independently for both; one buttline datum can be established for the module, two references from that datum are critical. In the decomposition discussed in Section 4.1.5.2, where only the keel alignment KC crosses a module break, no coupling among these two KCs is present.

[14] Recall buttline is a term for side to side, waterline is a term for up and down, and station line is a term for fore to aft.

4.2.5 Chains are the Building Blocks for DFC and Quantitative Analysis

The fifth property is that chains are the building blocks for formal assembly modeling analysis that utilizes the same mathematical basis, such as the Datum Flow Chain (DFC) defined in Section 3.3.3. Because the principles defined in Section 4.1.3 preserve the technical meaning of DFCs and tolerance chains, chains establish the structure for early quantitative variation analysis and development of the DFCs. Each link in the chain, an AKC or Part KC, is the building block for either an assembly-level DFC or a manufacturing-level DFC, respectively (as illustrated in Figure 4-14). The AKCs are input into a formal DFC analysis as defined by Mantripragada [1998]. The Part KCs are input for analysis of the fabrication process capability. Together these are the building blocks for a quantitative variation study. The chain representation can be applied in the concept design domain despite the lack of detail required to fully populate the DFC or all the links of a tolerance chain.

To illustrate this, Figure 4-15a shows the DFC for link 5 in the chain for the C-17 nacelle example PKC (content derived from [Cunningham]). The DFC links show the physical elements that dimensionally locate each part; constraint is provided by the element at the tail of the arrow on the part at the head of the arrow. Each link is labeled with the number of DOFs constrained by that link. Figure 4-15b shows just the DFC links that are associated with the degrees of freedom (DOFs) of the PKC. This DFC shows that link 5 in the graphical chain expands into four additional relationships (the links in the DFC), that are all the children of the higher level representation in the chain. In fact, there is also contribution in each of the five physical

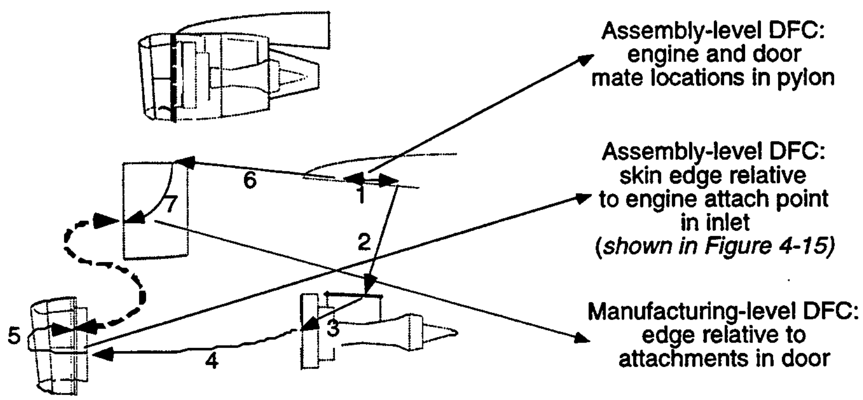


Figure 4-14. Chains are the building blocks for formal DFC and quantitative variation analysis.

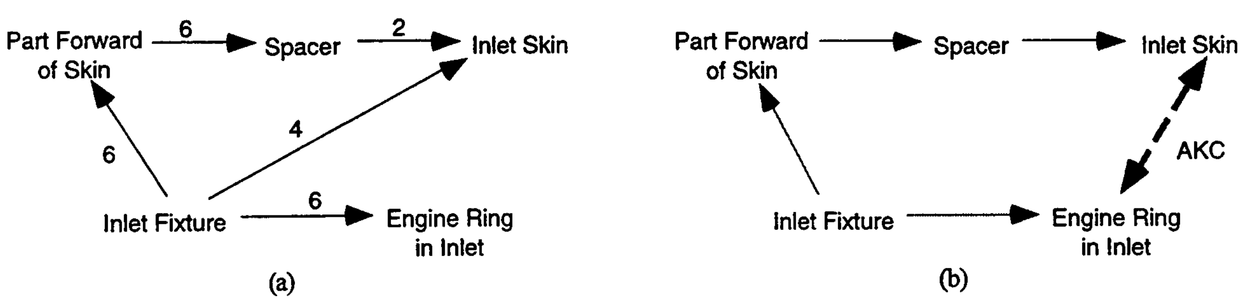


Figure 4-15. (a) Link 5 of the C-17 example PKC expands into an assembly-level DFC, and (b) shows just the DOFs that affect the PKC. This DFC shows how the inlet is assembled, so the fixture used in this process is present in the DFC.

elements in the DFC that could be revealed by further expanding this DFC.

The knowledge that chains are the building blocks for a quantitative analysis is important because the IPT can proceed knowing that it is driving toward quantitative analysis that will be able to occur sooner than if chains were not used to identify integral characteristics. So, chains not only allow the IPT to assess the integration issues of each concept qualitatively, they provide a clear roadmap to where critical quantitative analysis should be performed. Quantitative analysis will carry more weight in trade-offs, and a goal is to get to meaningful quantitative analysis sooner. Section 4.5 describes how to use the chain structure to develop a quantitative variation analysis.

4.2.6 Chains Illustrate Function Delivery in the Context of the WBS for Broad Communication in a Multi-disciplinary IPT

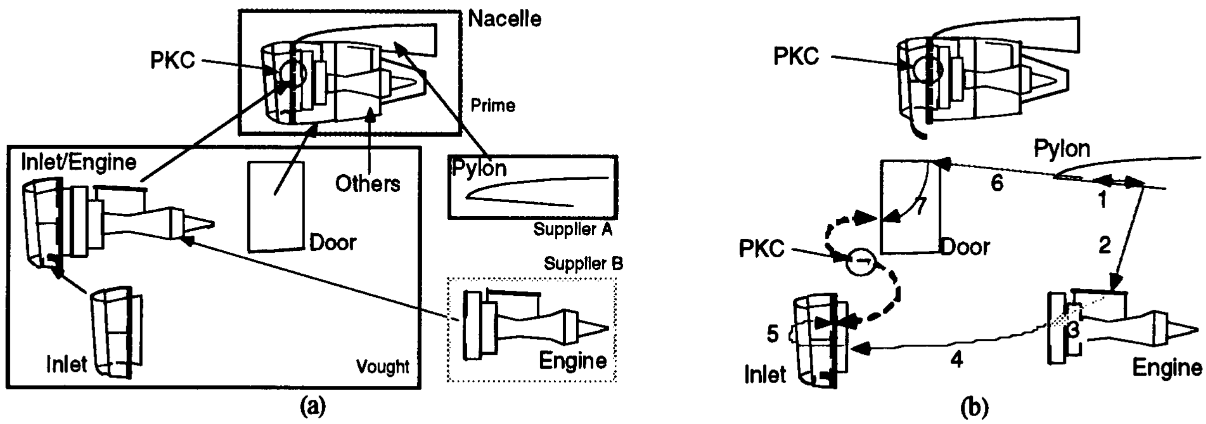
The final property is that chains illustrate function delivery in the context of the physical elements so technical and non-technical team members can relate specific physical elements and their decisions involving processes, suppliers, and technologies (recall these decisions are the drivers of physical decomposition). This applies the technical content of tolerance chains in a "low tech" version that has broad application across the IPT.

The examples above show the illustrative capability of chains: the functional-physical mapping depicted on representations of the physical elements. We can extend this to show broader technical and non-technical issues that must be shared in the 3D IPD environment. Figure 4-16 shows the decomposition of the C-17 nacelle with four colors that depict the supply chain; the green represents the prime developer who performs final assembly, and blue, yellow, and red correspond to three first-tier suppliers, including Vought.[15] The PKC is marked with a red circle. The chain is shown in Figure 4-16b with the link colors matching the supply chain. Each link is described in the table in Figure 4-16c with the type of KC it represents, the element in the hierarchy where it is delivered (hence the process), the supplier of each link, and the technology used. This linked list associates the technical content with the broader IPT decisions that influence the delivery of each link, and hence the end dimension.

4.3 Chain Metrics

Metrics are applied to the set of chains for each decomposition to identify the integral characteristics and estimate the integration risk associated with these integral characteristics. Once the IPT follows the chain procedure and utilizes the IM to depict interactions of multiple chains, it must systematically evaluate them to compare the candidate concepts and decompositions. This section describes two categories of metrics required for evaluating chains. The first type reveals the integral characteristics. The second type is used to estimate the integration risk associated with these integral characteristics. After the IPT follows the chain capture procedure, it uses these metrics to systematically evaluate the chains to compare the candidate concepts and decompositions. These metrics are qualitative in nature, but lead an IPT toward a quantitative analysis by indicating the highest risk characteristics that warrant the resources required to perform a quantitative analysis, as described in Section 4.5.

[15] as described in Section 1.1.



Link	Description	type	delivered in	supplier	technology
1	Relative position of the engine and door attach points	AKC	pylon assembly	supplier A	fixtured, and many assembly steps
2	Attachment of engine lugs to pylon	AKC	final assembly	prime	interchangeable lugs
3	Relative position of inlet attach ring in engine and engine lugs	AKC	engine assembly	supplier B	multiple mechanical assembly steps
4	Attachment of inlet to engine	AKC	inlet/engine mate	Vought assembly	matched holes
5	Relative position of skin edge to engine attach ring in inlet	AKC	inlet assembly	Vought assembly	fixtured, and many assembly steps
6	Attachment of door to pylon	AKC	final assembly	prime	interchangeable hinges
7	Relative position of forward door edge to hinges in door	Part KC	fabrication	Vought fabrication	composite lay-up

(c)

Figure 4-16. C-17 nacelle example PKC (a) decomposition and supply chain, (b) chain, and (c) a corresponding list describing the attributes of the links.

4.3.1 Chain Structure as an Indicator of Integrality

Recall that the fundamental measure of integrality is the degree to which a single function is shared among physical elements and their interactions. The degree of integrality must be measured in terms of the mapping of each characteristic individually. However, we are also aware that functions may be shared among the same elements, where their delivery is coupled or may conflict. Therefore, after each characteristic's integrality is assessed, its mapping interactions with other characteristics should be measured. Finally, because there are many characteristics, an aggregate measure of integrality should be derived from the combined mapping of all characteristics in a candidate concept and decomposition.

Three metrics are applied to each chain to measure the degree of integrality:

- mapping - the chain's "span" and "height" in the hierarchy
- chain coupling
- relation of chains to the production critical path, or other production system performance measures.

The metrics are then combined to create an overall Chain Structure metric for each KC by a monotone combination of the metrics. By assessing the combined chain structure, we seek to reveal the integral chains explicitly. The following describes the three metrics, then a qualitative scoring approach, and a means to combine the three metrics into a single modular/integral score.

4.3.1.1 The Mapping Metric

The Mapping Metric measures two attributes of the chain: its *span* and *height*. The span, illustrated in Figure 4-17a, is a measure of the *maximum* hierarchy level that the chain crosses the WBS. The span is one level below the root element, because the span is defined as the highest level with relationship among elements, and root element is the lowest element that contains all the end features. The metric is larger if the hierarchy level is higher, and indicates a higher degree of integrality because of the implied larger number of elements and their designers, suppliers, assemblers, inspectors, and so on, involved in delivering the KC at the root. The height, illustrated in Figure 4-17b, is the vertical distance in the hierarchy occupied by each branch of the chain. I assume that the bottom is always at the part level even if parts have not yet been identified. Larger height indicates more integrality due to longer communication links along the chain and different levels of perspective among the communicators. The height may differ in different branches of the chain, so we take the maximum level to measure the level of integrality. In order to measure the height, something must be assumed about frames in each branch of the chain. This can take the form of different options or specific reference frame assignments. Without any reference frame assumptions, only the span can be measured and the height should be assumed as the maximum.

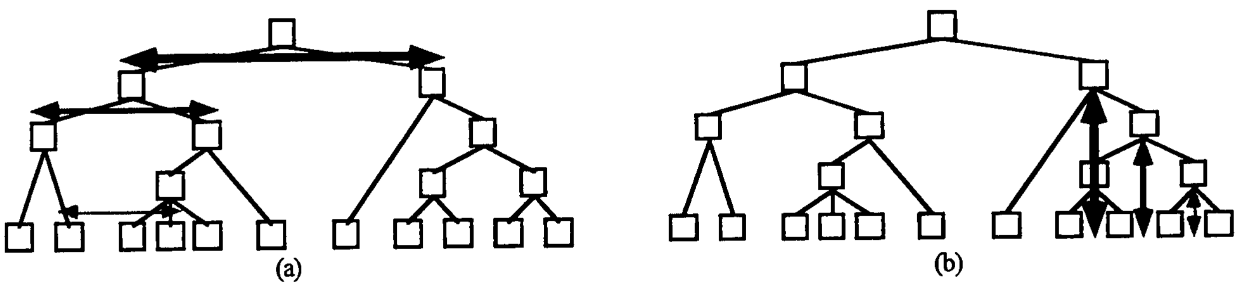


Figure 4-17. Two measures in the mapping metric: (a) span and (b) height.

Figure 4-18 shows the examples described in Section 3.3.2.3.2.2. The first example spans systems and is delivered at the height of a system. The second example spans modules and is delivered at the height of one module. The third example spans sub-assemblies and is delivered at the height of one sub-assembly. The fourth example breaks this pattern as it spans systems but is delivered at the height of one component in each system. By maintaining both mapping measures we can compare the degree of integrality in the fourth case to the other three more completely than just measuring if the function is delivered in 'x' number of elements.

At the highest two levels of the hierarchy I have found it useful to categorize KCs into four types:

1. Chain spans two or more systems, and at the height of at least one system (multiple modules in that system).

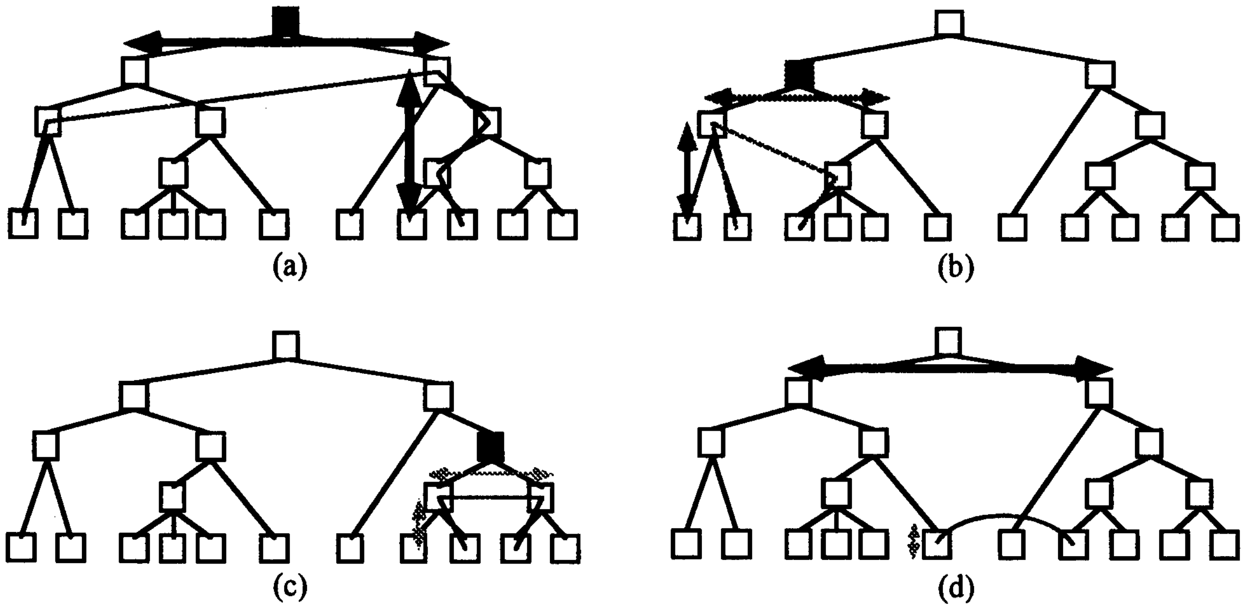


Figure 4-18. Four examples of span and height corresponding to the examples of Figure 3-16.

2. Chain spans two or more systems, but the height is at or below the module level in all systems.
3. Chain is delivered in one system but spans modules.
4. Chain spans less than the module level in one system.

The relation of each KC to these four categories will be shown below as an indicator of the combined integrality in the architecture of a candidate decomposition.

4.3.1.2 The Coupling Metric

Coupled chains are those that share the same interactions across elements and contain links in the same elements, as shown in the example in Figure 4-19 where the chains share three interactions. The Coupling Metric compares the mapping metrics of two chains that share at least one link. This metric allows us to increase the integrality of an otherwise modular chain if it is coupled to a chain with a high mapping metric score (indicating that it is integral).

4.3.1.3 The Critical Path Metric

When a chain is found to affect a non-product performance attribute, e.g. a performance measure of the production system, it is "integral" in that attribute as well. This category of metric allows the IPT to relate the integrality of product characteristics to interaction with other attributes

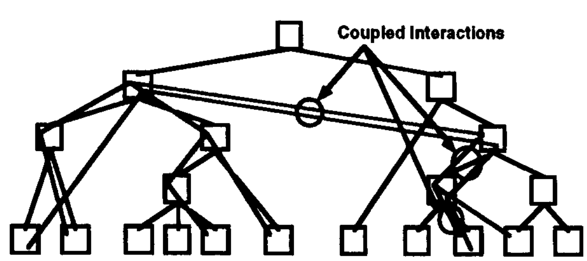


Figure 4-19. Shared interactions across elements indicate coupling.

outside the product domain. Critical path and its direct effect on cycle time is an integrality metric used in the examples in Chapter 5 and case study in Chapter 7. Cost is discussed briefly below but not used in directly in the examples and the case study.

4.3.1.3.1 Critical Path

The production critical path is a common measure used to manage the cycle time. Chains that lie on the critical path, like the example shown in Figure 4-20, directly influence the cycle time of the production system. The Critical Path Metric measures the combination of a chain's integrality and its potential impact on production span time. A critical path in assembly usually appears in the decomposition hierarchy as a set of elements occupying one branch of the tree. The critical path metric is calculated by counting how many links of a KC chain pass through elements on the critical path. In Figure 4-20, there are three such elements.

4.3.1.3.2 Example of Other Non-performance Production System Attributes - Cost

When the KC delivery failure would have a known, significant impact on cost, the chain is integral in the cost of the system. Some examples of what may be categorized as significant:

- special processing required to be repeated
- tear down of components
- irreparable - may be used but won't be able to be repaired in use
- unsalvageable - potential scrap late in production.

This metric is not included in the case study but is an example of the type of metrics that can be applied to identify integral characteristics. If the elements on the chain exhibit these characteristics, they have a tangible impact on cost that should be included in the integrality rating.

4.3.1.4 Qualitative Scoring Approach

The chain structure metrics are applied to each characteristic to rate its integrality. In this thesis a three level scoring - red for most integral, green for most modular, and yellow for in between - is applied to show how to apply a rating method to this analysis. This is the most simple rating possible, with other possibilities being numerical ratings with more delineation (five levels, ten levels, etc.) or some type of naming of the levels. The rating must reflect a spectrum that is more descriptive than just "modular" and "integral."

The three Chain Structure metrics are scored via the following:

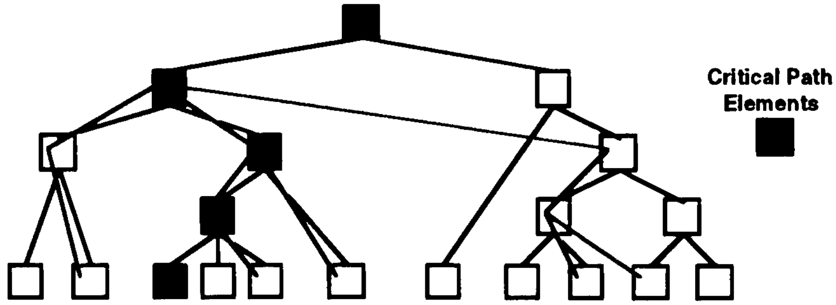


Figure 4-20. Interaction of a chain with the critical path.

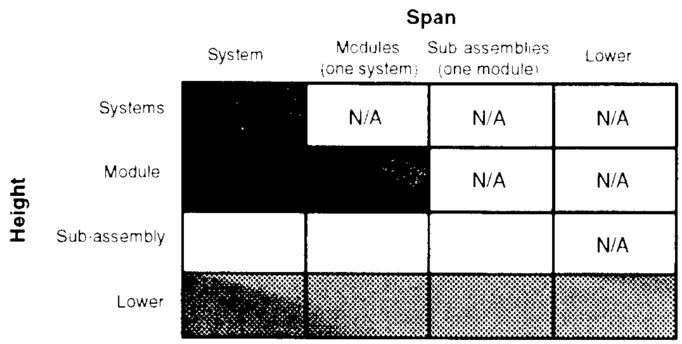


Figure 4-21. Rating table for the mapping metric.

- Mapping Metric: three level rating scheme for the Mapping Metric based on both span and height, as shown in Figure 4-21, where height is taken as the maximum of all branches spanned.
- Coupling Metric (CM): maximum Mapping Metric (MM) score of the chains to which a chain is coupled, as shown in Equation 4-1.
- More elements on the critical path indicate a higher value of the metric, as shown in Figure 4-22.

CM(Chain 1 or Chain 2) = max (MM for Chain 1; MM for Chain 2) (4-1)

Figure 4-23 relates the mapping metric scoring table to the four categories of KCs listed in Section 4.3.1.1. Category 1 is the most integral and always scores red. Categories 2 and 3 can take on a the full spectrum of ratings depending on how the KC is delivered in the individual systems. Category 4 never scores red.

Most companies have some type of risk assessment method to systematically analyze a problem qualitatively. At this stage the IPT is not measuring risk (yet), but the same type of thinking is

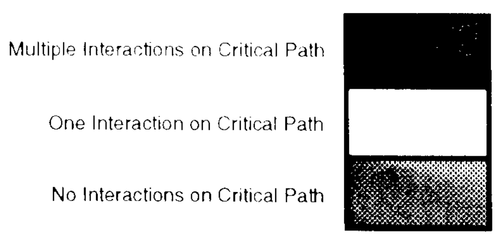


Figure 4-22. Rating table for the critical path metric.

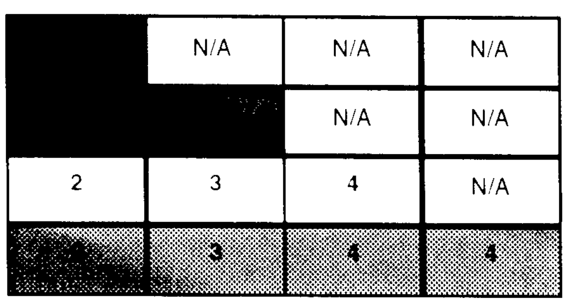


Figure 4-23. Integrality rating in the Mapping Metric corresponding to the four KC categories.

applicable for the purpose of rating the characteristics to identify those that are most integral. The goal is not to place a hard quantitative value for comparison but to categorize the characteristics, based on the metrics applied to their chains, to set priorities for the next step in the analysis. Because this remains a qualitative analysis, the team should specifically avoid false quantitative measures just for the sake of making the analysis more quantitative. This is the motivation for the approach I take here, which is purposefully not quantitative because meaningful quantitative ratings are not available.

4.3.1.5 Identifying Integral Characteristics

Based on the rating of each characteristic that results from applying the three metrics, a set of criteria are applied to determine which characteristics are deemed integral. These criteria depend to some extent on the risk philosophy of the company because the analysis remains qualitative. There are some fundamentals that should be followed in developing these criteria. First, an average of the ratings of the three metrics has no meaning and is not a sound method to identify the integral characteristics; e.g. a rating of red, green, yellow does not make a characteristic yellow. Instead, some metrics dominate others. Second, the Mapping Metric is the fundamental measure of integrality. If a characteristics scores integral on the scale of this metric, it is integral no matter what its score in the other metrics. If a characteristic is rated relatively modular in the mapping metric but is coupled to integral characteristics, it a candidate for being rated integral. Finally, a characteristic on the critical path also warrants consideration for being labeled integral.

In the case study in Chapter 7, I selected the following criteria for identifying the integral characteristics:

- all characteristics that scored red in the mapping metric
- all characteristics that scored yellow in the mapping metric and red on the coupling metric
- all characteristics that scored yellow in the mapping metric and red or yellow on the critical path metric
- all characteristics that scored green in the mapping metric and red on both the coupling metric and the critical path metric

An alternative would be to select those that score red in any metric. Even if this means all the characteristics are labeled integral, that is a viable approach. The purpose is not to discern among the characteristics *within* a single decomposition. The foremost goal is to discern *among* the many candidate decompositions by systematically comparing the architecture in terms chains that deliver the KCs. There can be decompositions in which *all* characteristics are integral; a rating system should not preclude this possibility.

4.3.1.6 Global and Quantitative Metrics of Integrality

This research focused on developing and testing chains as an indicator of the product architecture and metrics for measuring the architecture. The next step would be to develop a global product measure of architecture based on these metrics. The goal would be a meaningful lump score for a particular concept and its best decomposition for high level consideration of architecture, much like the lump score for an assembly that is the output of Boothroyd DFA analysis. This lump score should be based on the rating in the three metrics.

Other quantitative product level measures are available as well. These include the number of PKCs spawned by each KC, the number of coupled KCs, the number of chains on the critical path, the relation of the platform strategy to the KCs (whether the intended modular attributes are in fact modular), etc. None of these measures and their use were included in this work but have the potential for contributing to a global measure of architecture. This is discussed further in Section 8.4.2, Future Work.

4.3.2 Individual Chain Characteristics - Risk

Even in simple products it is likely that some critical functions will be delivered in integral characteristics. However, a high value of the chain structure metric does not guarantee integration risk. For this reason, I have developed a second set of metrics that highlight particularly risky technical, managerial, and organizational situations. This set of metrics is applied to compare the integral characteristics in different concepts and decompositions in terms of their integration risk. These metrics are:

- number of links in a chain (a technical complexity measure)
- number of organizational boundaries crossed by a chain (an organizational complexity measure)
- lack of robustness or novelty of technologies or processes relied on to deliver links in the chain, or degree of dependence on suppliers for such technologies (a strategy and capability impact measure)

4.3.2.1 Three Integration Risk Metrics

To measure the complexity of the chain we count the total number of elements and interactions on the chain. This is an indicator of how many sources of error can potentially lead to failure of KC delivery. More sources of error indicates a higher level of complexity. This metric has a potential pitfall in that one decomposition may be defined more levels than another. So, measuring the number of links in a chain defined down to the component level versus one defined only to the sub-assembly level would penalize the former, clouding a substantive risk comparison. A better approach is to normalize the metric in terms of a percentage of the components that are defined.

The latter two risk metrics measure risk associated with outsourcing and technology selection. A higher number of organizational boundaries crossed by a chain indicates additional interfaces that must be managed, each a source of error. Figure 4-24 shows the type of interactions that can create barriers to communication when organizational boundaries exist. In this example assume the teaming arrangement, where communication is expected to occur constantly, is set at the module level in each system. If the characteristic is delivered in a sub-assembly of one module that will be outsourced further, and the module level of the other, there is a barrier to communication, as indicated by the light line in the figure. The deliverer of the module is not assured to be in communication with the sub-assembly supplier in the other module. The heavy lines in Figure 4-24 indicate more drastic indicators of potential barriers, where the chain is delivered at the level of components in separate branches of the WBS.

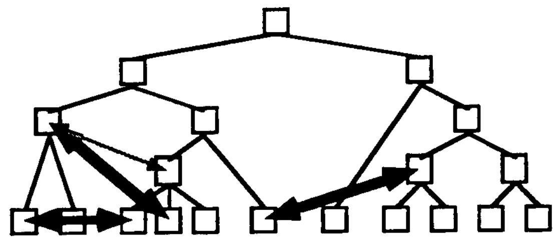


Figure 4-24. Types of organizational boundaries that indicate integration risk.

Suppliers are not typically selected, with the exception of perhaps teaming arrangements, in concept design but rather make/buy decisions are applied over time in product development. However, a strategy is typically thought out in this phase that will indicate where barriers could be when correlated to the chains in this way.

A higher number of risky technologies or technologies not controlled by the final assembler indicates uncertainties about performance in time, cost, or quality. In Fine [1998] and Fine and Whitney [1996], risks associated with outsourcing are categorized. Higher risk is associated with outsourcing integral items or those whose chains are coupled to other chains, especially when the source controls the key knowledge needed to deliver the chain. Again, the supplier strategy is typically in place during concept design so that the integral characteristics can be checked for this type of integration risk.

The technology capability is also measured on integral chains. Mature technologies pose little risk while new technologies pose substantial risk. Aligning technology development with the high risk integral chains can set investment priorities early in development for those technologies. In order from most mature to least mature, we can define the following characteristics:

- established process with relevant (analogous) capability data,
- established process without relevant capability data,
- developing process with funding prioritized,
- undeveloped process with funding prioritized,
- undeveloped process without funding prioritized.

4.3.2.2 Risk Rating Approach

As with the red-yellow-green scale applied to indicate the integral characteristics, the same scale provides a simple example of how to score the risk metrics. In practice other rating scales would be appropriate depending on the risk approach of the company. Consistency is the key to ensure that the IPT ultimately achieves differentiation in terms of the risks in different concepts and decompositions.

The complexity scale should match the normalized value of the number of elements in the product hierarchy. Red indicates half or more of the elements interact, green indicates one or a small percent interact, and yellow is the rating applied to cases that fall in between. Recall it is not important to differentiate which elements, as they will be measured in the other two metrics.

As indicated in Figure 4-24, different relationships on the WBS indicate different types of barriers on the chain. A score of green is reserved for no barriers, yellow for single tier barriers

like those represented by the slim line in Figure 4-24, and red for substantial barriers like those shown by the heavy lines in Figure 4-24.

A scale of a process's capability character was described above. If a chain is populated with all established processes, it would be rated green, developing processes would be rated yellow, and undeveloped processes are rated red. Recall that the Matrix of Dependency and Outsourcing [Fine and Whitney] establishes the relative risk for modular and integral elements of a system based on whether the integrator is dependent for knowledge or capacity. For any developing process that is outsourced, and lies on an integral characteristic, the integrator is dependent for knowledge, and therefore this represents a high risk position.

4.3.2.3 Combined Integration Risk Score

The three risk metrics are combined to identify high integration risk integral characteristics. In the case study in Chapter 7, the following criteria were used:

- red on any metric, high risk for the KC
- yellow on three metrics, high risk for the KC
- yellow on two metrics, medium risk for the KC
- red on any metric at the level of the system, red for the KC
- yellow on any metric at the level of the system, yellow for the KC

The integration risk metrics were applied in the case study to different process scenarios, which were accompanied by outsourcing strategies.

4.4 An Interaction Matrix of Chains

A matrix representation, called an Interaction Matrix (IM), assists in depicting the interactions captured in *multiple* chains. This representation is intended for use when there are more PKCs than a graphical chain representation can clearly present. This section describes the IM. I begin with a summary of another matrix tool from which the IM is derived, the Design Structure Matrix (DSM), and then describe the mechanics of the matrix construction. I then describe how specific attributes associated with the metrics can be shown in the IM.

4.4.1 Summary of the Design Structure Matrix

The DSM is a *matrix* presentation the interactions of *tasks* performed in a process [Steward, Eppinger et.al.]. [16] The tasks are arranged down the left hand side in the rows of the matrix and from left to right in the columns to form an NxN matrix (see Figure 4-25). The tasks are listed in the order they are typically performed in the process. The goal is to identify which tasks feed information to or receive information from other tasks in the process so iteration and feedback can be discovered. A mark (an 'X' in Figure 4-25) is placed in the row of the task that receives the information, and in the column of the task that provides that information. By this convention interactions above the diagonal represent where *feedback* and hence iteration occurs in the process, while the feed-forward region is below the diagonal. In Figure 4-25, tasks D, E, and F (among others) likely will have to be repeated one or more times because they receive

[16] DSMs are similar to "N2" diagrams used in systems engineering.

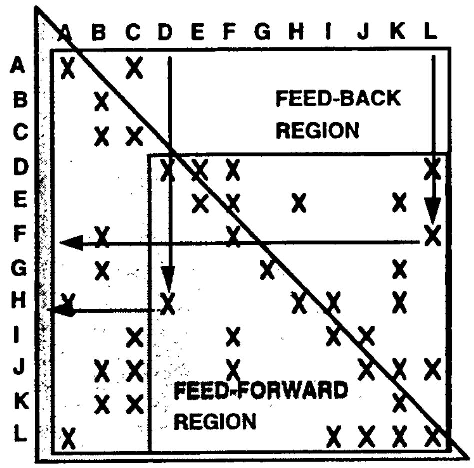


Figure 4-25. DSM representation of information flow (Figure by Dr. Dan Whitney [Eppinger et al])

information from tasks performed later in the process. Once these relationships are documented, the process tasks can be reordered using the insight into tasks that must be performed sequentially, those that can be performed independently in parallel, and those that are interdependent and must be performed concurrently; this latter set is grouped as a block on the matrix diagonal. The process can be improved by eliminating long-feedback loops, performing the correct tasks in parallel to shorten the overall time, and clustering these interdependent tasks so that iteration is conducted correctly.

The DSM has advantages over other methods such as Program Evaluation and Review Technique (PERT) in that iteration in the process is clearly depicted in a more compact form than PERT and other flowchart methods. In addition, the matrix representation allows for the application of algorithms based on matrix manipulation to re-order tasks into an optimal sequence where information availability is maximized [Gebala and Eppinger]. The matrix can be populated with numerical data representing the time of each task, the percent of the work that is likely to be repeated in an iteration step, the number of iterations that are likely, and the strength of the interaction to improve this re-ordered process [Eppinger et al and Krishnan et al].

Two further applications of the DSM have been investigated to a lesser degree than the task ordering application. The first lists organizations in the rows and columns and notes degrees of interactions between them on a particular development program. The organizations that interact the most can be clustered to into appropriate teams, and where there are broad interactions among all organizations the need for an integration team is recognized [McCord and Eppinger, on-going research of Browning in LAI].

The second variation to the DSM is more applicable to the work presented here. Physical elements of the system are represented in the symmetric rows and columns and physical interactions between them are represented in the matrix elements. Interactions that have been modeled include spatial, energy, information, and material [Pimmler and Eppinger]. This type of "physical interaction matrix" has the potential to show the interactions among physical elements indicated in chains, allowing multiple chains to be represented in a single tool. The remaining

sections describe the development and application of an IM for assemblies for use in assessing the architecture of different physical decompositions.

4.4.2 An Interaction Matrix of Assembly

In a matrix representation of assemblies there are two characteristics that need to be reconciled:

1. the physical grouping of parts into components, which are connected into sub-assemblies, modules, and systems, and are finally assembled into the product, as shown in a WBS
2. the shared delivery of function in two or more branches of the WBS that rely on interactions among the physical elements that lie outside the tree structure but also must be managed, as indicated by chains that span modules, systems, etc.

The challenge is to find a single representation that allows both characteristics of assembly to be represented clearly. The goal of the IM is to make both attributes equally explicit in a single representation, and to support a systematic method for identifying those interactions that are critical.

4.4.2.1 Representation of Assembly Tree in an Interaction Matrix

The task order in the DSM rows represents the order that tasks are performed or information is delivered in a process, with overlapped and concurrent tasks determined by block groupings. As described above, physical parts are not added one by one in many assemblies, but are assembled in a hierarchy of elements represented in a WBS. Therefore, in the IM, "sequence" must be represented using something other than the order of the parts in the matrix rows. The selected approach is to show the assembly tree as blocks along the diagonal in a symmetric matrix of a selected layer of elements in the tree (e.g. the components if the system has been decomposed that far, or a higher level of elements if it hasn't been), so sequence is represented by nested block groupings of the matrix elements as opposed to the row order. In this application the row order of the parts has no meaning apart from the blocks representing the tree.

Figure 4-26 shows the conversion of a simple assembly tree into a matrix representation. There are ten sub-assemblies, four modules, and two systems in the assembly of this product (see Figure 4-26a). Figure 4-26b shows the components arranged in a 10x10 matrix. Figure 4-26c shows four blocks on the diagonal that represent the sub-assemblies in the tree; from here on the column headings are dropped due to their redundancy, while the diagonal is marked with a gray line. Figure 4-26d shows the two module blocks that encompass the appropriate sub-assemblies.

The construction of the matrix represented in Figure 4-26 represents a "bottom-up" use of the tool, where, sub-assemblies, modules, etc. (the entire decomposition) were previously determined. In a "top-down" environment where the product is decomposed into systems, then modules, sub-assemblies and components, and finally specific parts, the same representation can be used with the lowest known elements listed as the rows and all levels in the tree represented with matrix blocks. The latter describes the application of greatest interest - the concept design phase.

4.4.2.2 Interactions in the Interaction Matrix

Interactions among the IM elements are shown off the diagonal like in a DSM, with the positions

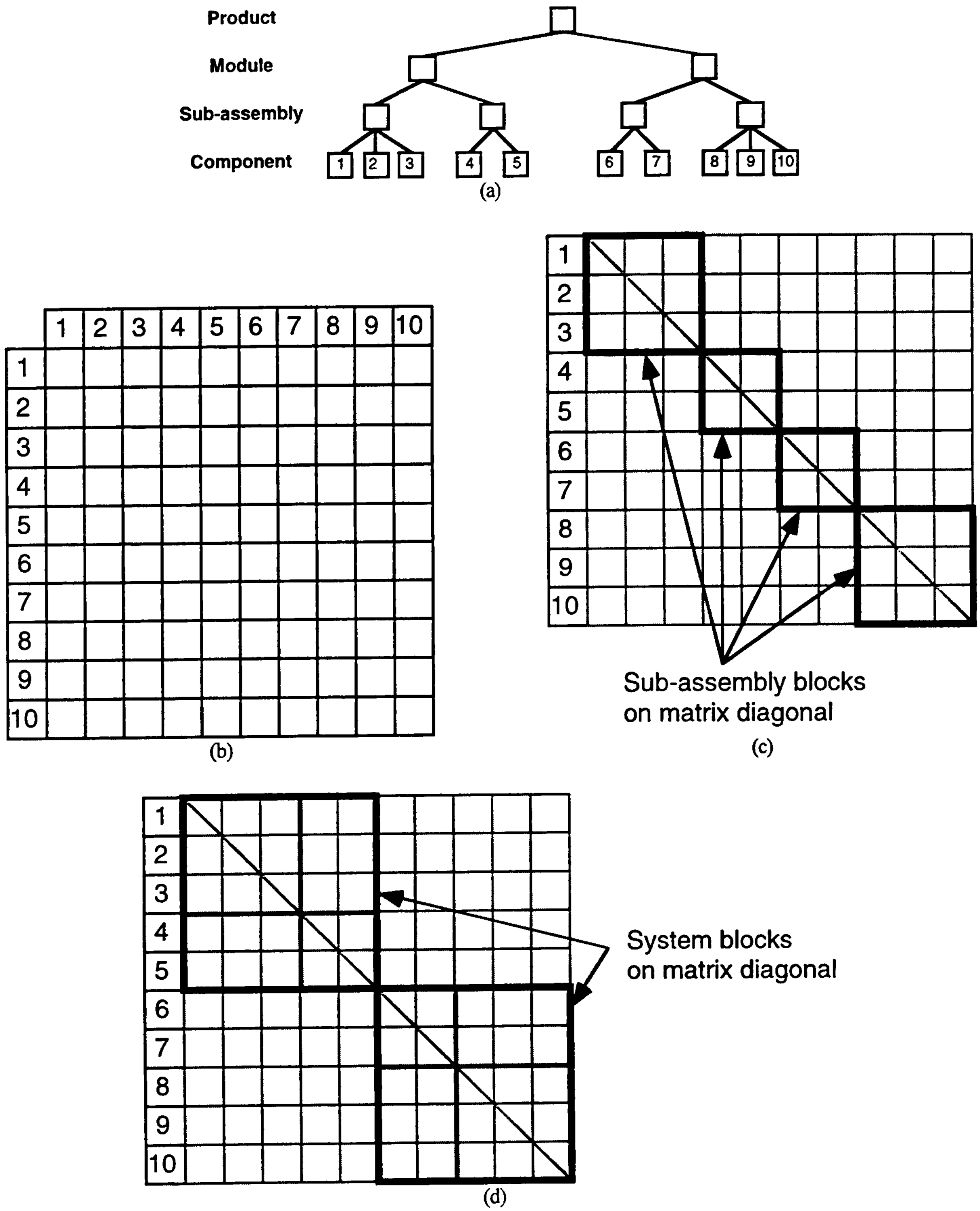


Figure 4-26. Conversion of (a) an assembly tree of into a 10x10 matrix of (b) components, in (c) sub-assembly blocks and (d) module blocks.

of the interactions in the blocks in the matrix showing the chain interactions among elements. For example, Figure 4-27 shows how the four chains depicted in Figure 4-18 can be represented in an

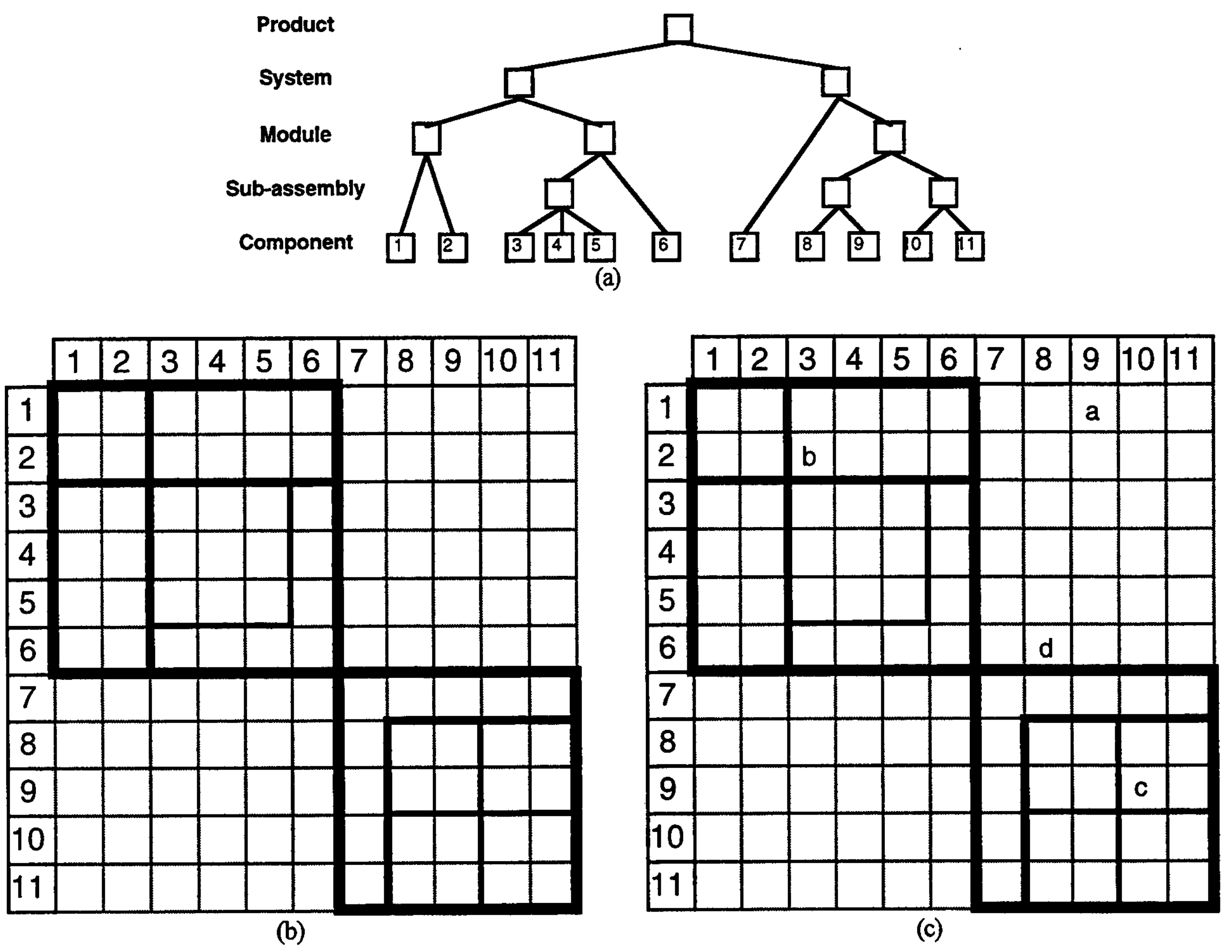


Figure 4-27. Conversion of (a) the WBS in Figure 4-18 into (b) an IM with (c) the interactions indicating the span of the four chains corresponding in letter to those in Figure 4-18a, b, c, and d.

IM. Figure 4-27a shows the WBS used in Figure 4-18 with the components numbered, and Figure 4-27b shows the corresponding IM with sub-assembly, module, and system blocks shown. Figure 4-27c shows the interactions (with a letter corresponding to the example in Figure 4-18) in the matrix. Note two points here for clarity:

- only the upper portion of the matrix above the diagonal is populated with interactions (at this point, more regions will be utilized later)
- the span of interaction across the tree is shown by placing an interaction only in the block that intersects the elements containing the end features; height is not depicted in this case.

4.4.2.3 Relation of the Chain Structure Metrics to Mapping in the Interaction Matrix

The IM can be exploited to simplify the mapping of multiple chains. This section relates the IM to the three integrality metrics.

4.4.2.3.1 Mapping Metric

The regions above and below the diagonal have specific meaning in the DSM once a convention is established for feedforward and feedback between the ordered tasks. In the IM we are bound by

no such convention, i.e. regions above and below the diagonal are available for any interactions. This gives tremendous freedom to the choice of how interactions will be displayed.

The mapping metric can be related directly to the IM because the interactions fall in the blocks that represent different levels in the hierarchy, as shown in Figure 4-27c. If we limit ourselves to a consideration of the top two hierarchy tiers, i.e. systems and their modules, regions of the matrix can be specifically dedicated to the four categories described in Section 4.3.1.1.

Figure 4-28a shows what I call a *KC Matrix*: an IM showing the chain interactions at the top two levels of the hierarchy, categorized into four types, with regions of the matrix dedicated to each type. No interactions of a characteristic's chain will lie outside the region of the matrix for that category. This allows for a clear depiction of the different types of KC mapping as documentation of the interactions at the top two levels.

The next step is to represent the height associated with the chain branches that lie in each module. Only the chains that lie in the module are considered. Figure 4-28b shows how I dedicate the regions of a *Module Architecture Matrix*: an IM showing the chain interactions in an individual module, with types 1 and 3 (the ones with interactions with other modules of the same system) plotted in the upper region and types 2 and 4 plotted in the lower region. Here categories 1 and 3 are mapped together because these represent chains that have interactions with other modules in the same system. Categories 2 and 4 are delivered in the one module being investigated of the system, though in the case of category two there are interactions with other systems. The matrix can include sub-assemblies, components, parts, or part features depending on the level of definition of the decomposition.

4.4.2.3.2 Coupling Metric

The IM can be used to systematically identify coupled chains. Figure 4-28c shows where coupling resides in the KC Matrix. Chains with common interactions across the same elements

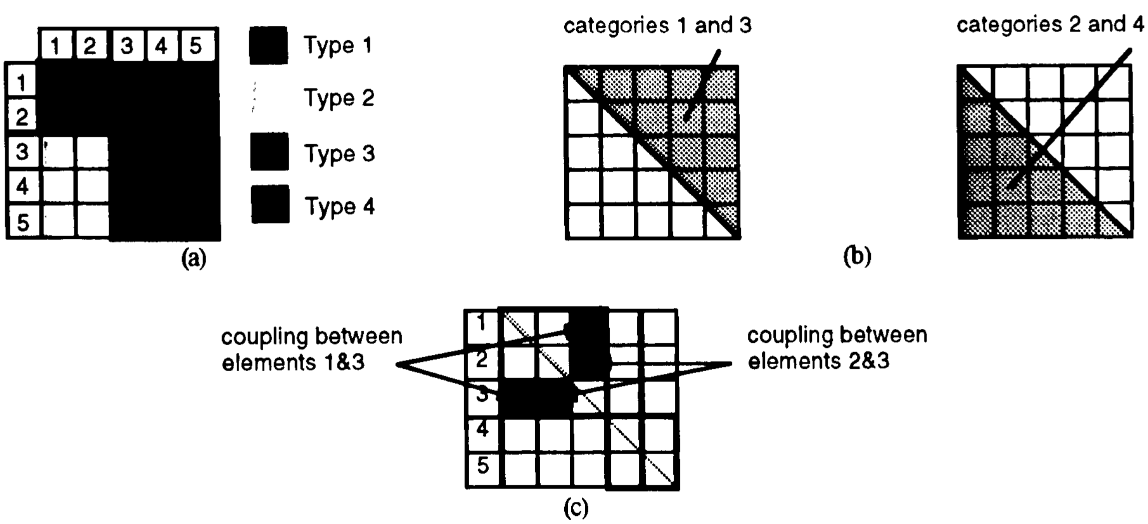


Figure 4-28. Use of the IM to indicate mapping and coupling. (a) Regions of the IM where different categories of KCs will be indicated in the KC Matrix. (b) Regions of the IM where different types of KCs will be indicated in the Module Architecture Matrix. (c) Coupling indicated in a KC Matrix.

will be mapped in the same blocks of the matrix and in blocks symmetric across the diagonal. Figure 4-28c shows interactions that cross the modules in the same or different systems.

By marking only the interaction(s) across the largest span of the tree we will identify chains that are coupled across the module boundaries. All links and a set of nested IMs will be needed to recognize coupled chains at lower levels in the module (i.e. coupling across sub-assemblies). Subsequent levels of coupling can be identified using the Module Architecture Matrix, and eventually as we map less and less chains within each element the chains themselves can be used to identify the coupling. This will be a recurring process until the entire decomposition is completed, which may not be achieved during concept design.

4.4.2.3.3 Critical Path Metric

The critical path can be mapped onto the IM. Any element that lies on the critical path will have its block along the diagonal marked, as will off diagonal blocks of higher level elements. Any chain interaction indicated in a shaded region lies on the critical path. For example, recall the critical path indicated in Figure 4-20. Figure 4-29 shows the corresponding IM with the appropriate regions of the matrix shaded to show the critical path. The appropriate regions indicated as being on the critical path in Figure 4-20 are:

- component 3, so the box on the diagonal for component 3 is shaded
- the joining of components 3, 4, and 5 into a sub-assembly, so all blocks off the diagonal that interact these components are shaded
- the module containing component 3, so all off diagonal blocks in the module block are shaded
- the system containing component 3, so all off diagonal blocks in the system block are shaded, and
- final assembly of the product, so all blocks outside the two system blocks are shaded.

4.5 Quantitative Methods

Quantitative analyses tend to carry more weight in trade-offs among the many competing objectives in product development. As described in Section 3.3.3, statistical variation analysis is fast becoming an industry standard for quantitative producibility analysis during the design process. Companies continue to apply this analysis earlier in design, as early as product layout

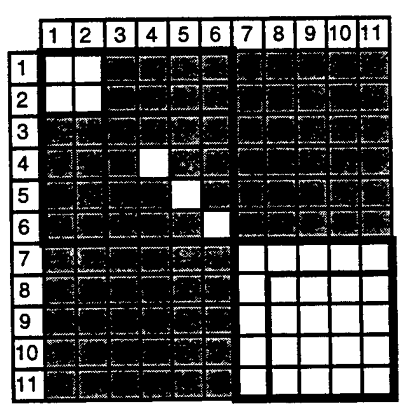


Figure 4-29. Critical path indicated in an IM of the example in Figure 4-20, where shaded regions lie on the critical path.

stages if the necessary information is available to conduct the analysis. This section describes the information required for such analysis in a commercial software package called Variation Simulation Analysis (VSA), the barriers to such analysis, and how chain analysis can help overcome in new designs that do not have the required information.[17]

VSA is one of many potential techniques that could be described in this context. I chose to discuss VSA in particular due to personal working knowledge with the software and its increasingly widespread use in the automotive [Sweder and Pollock], aerospace [Behan], and other industries with large and small commercial and defense products. VSA is not appropriate to all variation problems, so other techniques for variation analysis should be gauged against the same question posed here: what information is required for the analysis, and how much effort needs to be expended to make the decisions to create that information?

4.5.1 VSA as an Early Quantitative Analysis Tool

VSA is a 3D tolerance analysis program that performs Monte Carlo simulations by varying product tolerances of a user specified distribution and analyzing interfacing features of the product [VSA].[18] A barrier experienced by companies' implementation of such analysis is the perceived level of effort required to conduct variation analysis. VSA can be performed on a full geometric model of the product that includes the following:

- an assembly tree,
- assembly sequence,
- all locators used on all parts and elements in the assembly tree,
- definition of fixtures,
- definition of measurement points, and
- representation of all variations (process capability) in the geometry of the product and fixtures.

This represents a formidable task on a complex product.

VSA can also be performed on a dimensionally representative skeletal or layout model of the product with limited number of variations represented. The choice of which variations to represent is critical - the method can not indicate the critical processes if the input does not contain information about them. In addition, the software still requires the following:

- complete decomposition down to the level of parts and features,
- an assembly tree,
- assembly sequence,
- all locators on all parts and elements in the assembly tree,
- fixtures, and
- measurement points.

[17] Section 5.3 explains how Ford Motor Company is in a position to overcome the barriers to this analysis.

[18] I wish to thank Variation Systems Analysis, Inc. for the opportunity to evaluate the software under a no cost academic evaluation license.

So even when companies recognize that the software can be used quite early in design, prior to full definition of the geometry and before all process capabilities are known, there is a barrier to its use in that a great deal of information about the product is required.

4.5.2 Barriers to Use of VSA in Concept Design

As described in Section 3.2.1, concept design is a phase of rapid evolution and generation of concepts where time and resources are valued commodities that directly limit the search space for potential design solutions. New analyses injected into existing design processes must compete for these valuable time and resources. While most companies agree that more should be done in concept design before major commitments are made, the realities of decreasing product development time, competition among a company's many development activities, limited resources across the company, etc. will continue to require that concept design analyses be implemented rapidly without requiring dedicated information be created for their use.

This is the principal barrier to the use of VSA in concept design. Information like a full decomposition, sequence, locators, and fixtures are not all necessary to the same degree for other analyses like manufacturing system cost, cycle time, etc. (though these analyses may be improved by the additional information). If VSA or any quantitative variation analysis process is to have impact in a rapidly evolving concept design, which may iterate in hours or a few days, it must be able to generate results in less than the time needed for that iteration cycle. If a full decomposition, locators, etc. all must be defined for each evolution of a concept to attain the results of VSA, it will fail to meet this iteration time window and will not earn a place in concept design evaluation.

4.5.3 How Chains Can Overcome Barriers to Quantitative Variation Analysis

Chains can simplify variation analysis by reducing the information required to conduct meaningful variation analysis. First, the high risk integral characteristics (or all integral characteristics) are the subjects requiring quantitative variation analysis, as identified by applying the chain method and metrics. The chains also indicate the elements that share in the delivery of each characteristic and show all dimensional relationships whose variation should be considered. Only the locators of the elements in the chain and capability of the relationships represented in the chains need to be included in the quantitative analysis.

The 767 Horizontal Stabilizer Upper Skin sub-assembly case described in Section 5.4 shows how chains led to a structured but limited scope quantitative variation analysis of a rough product layout with a limited amount of information created for the analysis. Section 7.4 discusses how quantitative variation analysis should be pursued following the architecture insight gained from applying chains in the JSF case study.

4.6 Chapter Summary: Relation of Chains to the Research Themes and Their Application in the Examples

Chains are used to reveal the integral characteristics and integration risks. After the metrics are applied, all of the following can be documented as the architecture of a candidate concept and decomposition:

- a summary of the architecture: category of each KC and a KC Matrix
- a list of the integral KCs and coupled KCs
- risk assessment of each integral KC
- the chain for each high risk integral KC, with the supplier, process, and capability information noted (as it becomes available)
- Module Architecture Matrices for each module containing a high risk integral KC
- results of quantitative analysis
- mitigation plans.

Because they reveal such in-depth information about the architecture, chains are the backbone of the two research themes in this thesis. First, chains provide a map from the physical domain to the effects physical decomposition decisions have on function. Chains show the physical elements that deliver each KC, derived from a critical function (KPP). In this way chains are applicable as a measurable attribute of functional-physical mapping, and therefore an indicator of the architecture of each candidate concept and decomposition. This analysis complements the models from design theory by reflecting the impact of IPT decisions that alter the physical decomposition to the resulting complexity in the functional to physical map. With this approach, the functional-physical map represented in the design models is more accurate and more applicable to product development in IPTs. Chapter 5 utilizes chains to describe architectural issues in four examples, including the 767 Horizontal Stabilizer case that shows how chains guided me from a process design problem to a simplified quantitative variation analysis of a candidate solution.

The second theme is that chains give structure to the 3D IPD process, as described in Chapter 6. Chains form a basis around which an agenda for decomposition and architecture choices can be made in concept design. Chapter 7 presents the in-depth Joint Strike Fighter case study, an examination of a complex product decomposition problem as it unfolded in concept design in the context of the 3D IPD environment.

5. Examples of Physical Domain Decomposition and the Architecture Insight From Chains

This Chapter describes four examples of technical and strategic trade-offs in the context of chains. Each example involves integral characteristics that are in conflict with a strategy better suited to a product having modular characteristics, and hence involve integration risk. Section 5.1 describes a contrived example of KCs in a two-drawer chest of drawers. Section 5.2 describes a high level aircraft decomposition issue in conflict with a teaming arrangement. Section 5.3 describes an architecture trade-off in light trucks interrelated with manufacturing strategy issues. Section 5.4 describes decomposition options of an aircraft horizontal stabilizer for the purpose of simplifying a process redesign. Section 5.5 lists several examples in the literature that involve architecture trade-offs. Section 5.6 summarizes the combined findings from these examples.

The C-17 nacelle example that has been utilized to this point indicated several issues about chains, including:

- the surprising number of elements and interactions that play a role in the delivery of a seemingly simple characteristic
- chains' ability to reveal the relative integrality of a characteristic
- how the links in a tolerance chain and a graphical chain look the same and are derived from the same basis, and further can be populated with quantitative information or qualitative information like suppliers and processes that deliver each link
- the idea that the chain builds the structure for quantitative study of the delivery of each link with Datum Flow Chains (DFCs).

The goal of this chapter is to convince the reader that the same issues can be found in many types of products, in many companies (different industries and countries), and in commercial and defense products. Table 5-1 lists the four examples to be discussed in this chapter, the Joint Strike Fighter (JSF) case study to be discussed in Chapter 7, and the C-17 example, and their relevance to the research, coded as follows:

1. explanation in terms of the chain procedure
2. multiple decompositions
3. coupling
4. integrality metrics
5. qualitative risk metrics
6. quantitative variation analysis
7. expansion of the chain structure to DFCs

Table 5-1
Examples and Case Study Relevance to the Research

Example/Case	Sections	1	2	3	4	5	6	7	8	9	10	11	12	13
Two-drawer chest	5.1	✓	✓	✓	✓				✓	✓				
Airbus 3XX	5.2				✓	✓				✓				
Ford Light Trucks	5.3		✓		✓		✓		✓		✓	✓		
Boeing 767 Horizontal	5.4		✓	✓	✓		✓	✓	✓		✓	✓		
Joint Strike Fighter	Ch 7	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓
C-17 Nacelle	Ch 1, 4	✓						✓		✓			✓	

8. manufacturing strategy
9. supply chain strategy
10. technology strategy
11. platform strategy
12. supportability strategy
13. full 3D IPD setting of the method (Chapters 6 and 7, JSF case study only)

The reader who feels comfortable with the chain procedure and metrics can proceed to the examples discussed in Sections 5.2-5.5, which show the chains' ability to reveal integration risk associated with diverse types of strategic issues. The simple example in Section 5.1 is provided to develop the level of comfort with the concepts discussed in Chapter 4 in the context of product with which the reader should be quite familiar. The example in Section 5.1 also shows chains for PKCs with more than two end features.

5.1 Two-drawer Chest

This example describes two ways that a cabinet with drawers could be decomposed for assembly. The object here is to explore multiple chains and decompositions in an environment where the reader is highly familiar with the product, at the risk of applying the concept to an overly simplistic example. The two major points to take from this simple example are (1) the execution of the method and resulting graphical presentation of chains and (2) the applicability of the approach to a the debate among a variety of strategic issues despite very little definition of the product. Two possible decompositions described below result in different chains (with different degrees of integrality and coupling), and therefore have different impacts on design, manufacturing, and supply chain strategy. The method is described both in terms of a set of generic chains where nothing is assumed about the reference frames, and then with a set of assumptions that lead to assignment of some of the reference frames.

5.1.1 Description

The example here is a two-drawer chest, e.g. a two-drawer file cabinet. The example below focuses on what are posed as the three KCs:

1. PKC #1: the alignment of the two drawer fronts relative to each other (to prevent rubbing contact of the drawers that would prevent closure and to provide an aesthetically pleasing look - see Figure 5-1)

2. PKC #2: the alignment of drawer sides and slides (to minimize the force required to slide the drawers in and out); this leads to PKC #2L for the lower and PKC #2U for the upper.
3. "appearance KC": the finish on the top and drawer fronts.

Figure 5-2 shows a key of the cabinet parts and symbols.

5.1.2 Decomposition 1: Integral Drawers.

Figure 5-3 shows decomposition 1, and indicates a hierarchy with the levels "product", "module", "sub-assembly", and "part." Each drawer module contains the body and front (it is considered a single unit in decomposition 1, though it potentially could be decomposed further at a later phase), which then go to final assembly. The left and right slides are to be assembled to the sides to form the cabinet side sub-assemblies. Then the cabinet sides and top are to be assembled into the cabinet frame module. The drawers are to be slid into the cabinet at final assembly and finishing to complete the product. Step 1 of the chain procedure involves identification of the elements containing sub-sets of the end features, and identification of the root element:

- PKC #1: the drawer fronts are members of their individual drawer modules, and the product is the root element.
- PKC #2L (#2U is similar): the drawer sides are members of the lower drawer modules; the lower slides are members of their individual side sub-assemblies, and are constrained relative to each other in the cabinet frame module; the product is the root element.

5.1.2.1 Example Chain

I begin with the chain for the drawer front spacing on the left end only; this is simpler to map than the entire chain for PKC #1 but has similar content. Figure 5-4 shows the gap of interest, the relative position of the left end of the top surface of the lower drawer to the left end of the lower surface of the upper drawer - the gap at the left end. The two representations in 5-4 are equivalent, with both shown for clarity. The curved line notation at left is the PKC representations used in graphical chains.

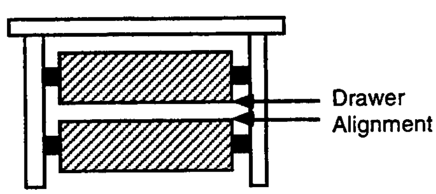


Figure 5-1. PKC #1: drawer alignment.

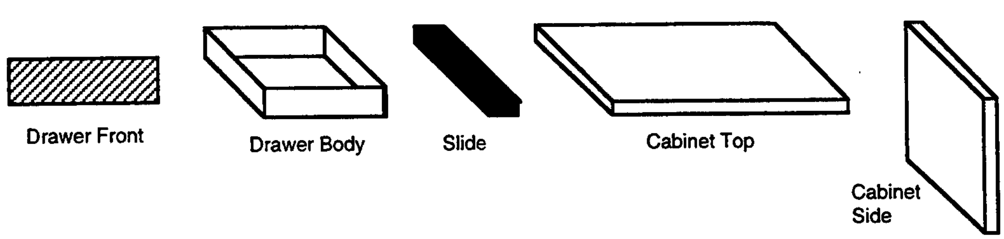


Figure 5-2. Key of cabinet symbols.

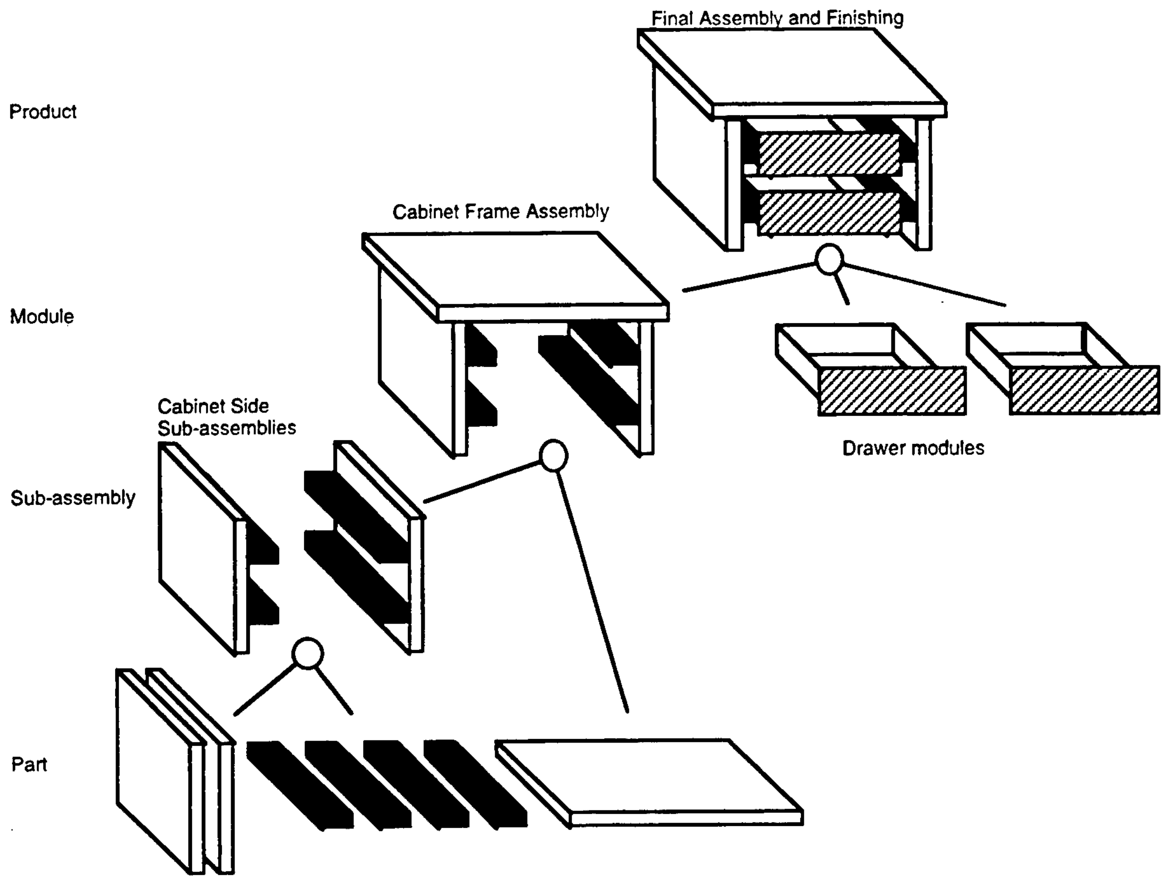


Figure 5-3. Two-drawer cabinet decomposition 1.

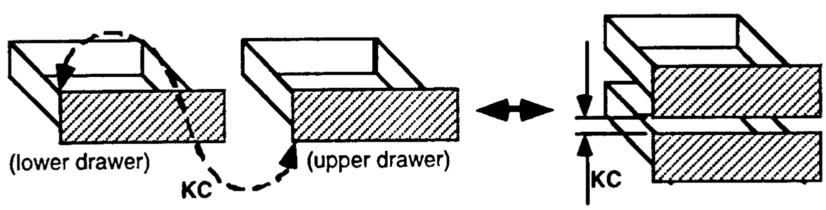


Figure 5-4. Gap at the left end of the drawers.

We begin with the generic chain. Following the steps in Section 4.2.2, Figure 5-5a shows the chain that starts with the root link between the module reference frames, and has two branches with a link in each module from the reference frame to the end feature.

If we make the assumption that the drawer reference frames at the module level are assigned to the drawer sides at the features that will slide on the slides (i.e. that assembly is accomplished simply by sliding the drawers onto the slides, as opposed to locating the drawers and adjusting the slides to them), then the chain in Figure 5-5b results. This is an example of case (b) in step 2 of the chain capture procedure, where the root link lies in a third element. The relationship between the drawer reference frames is contained in three links: one representing the spacing of the two slides on the left side, and one link from each slide to the corresponding drawer side. In this case, the reference frame is assigned to the drawer side, and this is the lowest level of

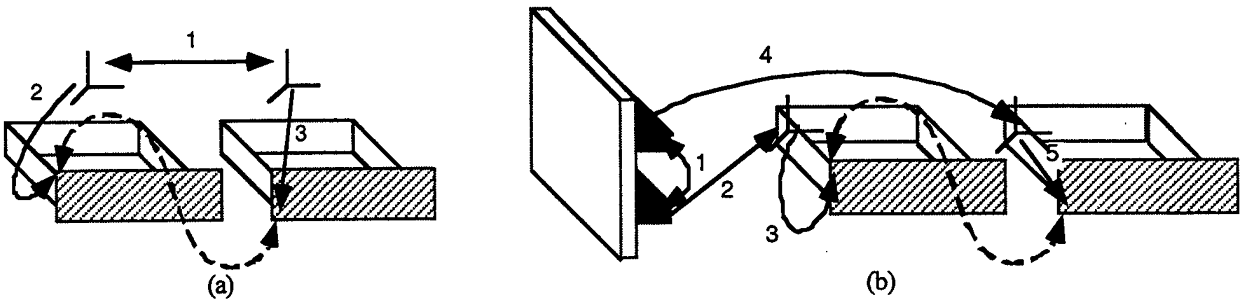


Figure 5-5. Chain that delivers the gap at the left end of the two drawers, (a) generic case and (b) with the assumption that final assembly is accomplished by sliding the drawers onto the slides. Note: this is not a PKC listed above but a simple starting point to illustrate how chains are documented.

decomposition in that branch, so the final link in the branch is from that reference frame to the end feature.

5.1.2.2 PKC #1

The chains for the actual PKCs are more complex because the reference frames that determine the complete orientations of the drawers must be represented. PKC #1 is not just the gap at one end or the other but the complete gap, so position and rotation degrees of freedom (DOFs) are all important. The chains described below show that four issues can alter the drawer alignment. One is a poor connection between the slide and drawer side, such as the extreme case where the drawer is off the slide and skews the drawer orientation. Figure 5-6 shows how drawer misalignment can occur three other ways, and the construction of the drawer in each case (front of the drawer body is represented by the heavy dashed line): a) slide misalignment with a properly constructed drawer (Figure 5-6a), b) a drawer body that is not square (Figure 5-6b), and c) poor alignment of the drawer front relative to the body even if the slides and drawer body are aligned (Figure 5-6c).

Figure 5-7 shows these effects in chains. The generic chain is the same as that shown in Figure 5-5a, but the reference frame denoted must account for the full orientation of the drawer and drawer front. Figure 5-7a shows the chain when we assume the drawers are attached directly to the

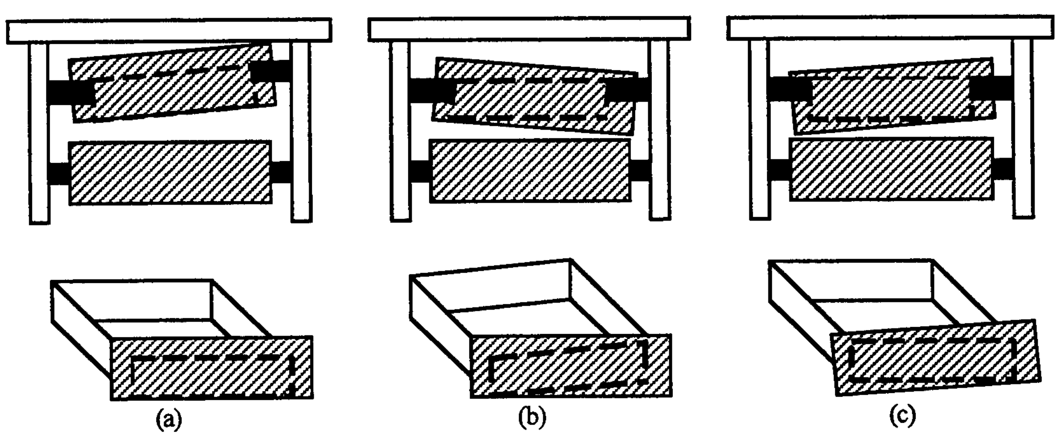


Figure 5-6. Three sources of poor drawer front alignment, a) slide misalignment with a properly constructed drawer, b) poor alignment of the drawer body, and c) poor alignment of the drawer front relative to the body even if the slides and drawer body are aligned. PKC #2 is affected by the first two but not the third.

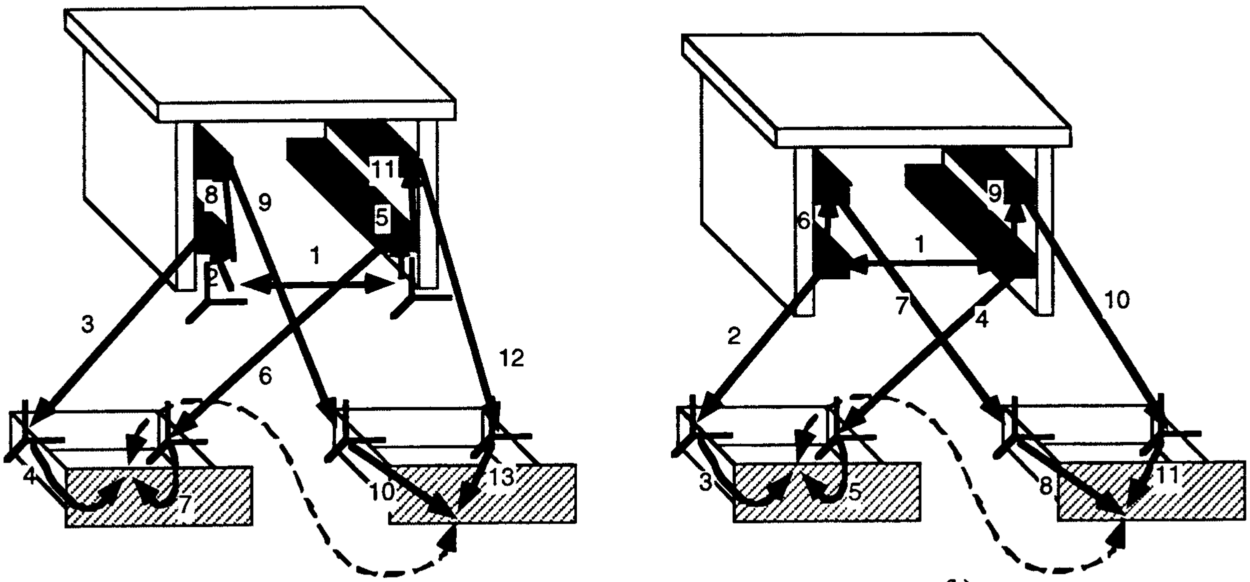


Figure 5-7. Chain that delivers PKC #1 for decomposition 1 with (a) the assumption that final assembly is accomplished by sliding the drawers onto the slides and (b) the assumption that the cabinet side reference frames are assigned to the lower slides. Link #1 is the root link, which lies in the cabinet frame module.

slides. Note that the chain now includes 1) the relationship of the two cabinet side assemblies' reference frames as the root link, which is a link in the cabinet frame module, and 2) the relative position of the drawer slides to those reference frames. The reference frame used to orient each drawer is shared by the two sides, so the chains split apart to each side and come back together at the drawer body. Figure 5-7b shows the chain if we assume the cabinet side reference frame is in one of the slides, e.g. the lower slide in each cabinet side. Links 1-5 determine the orientation of the lower drawer, link 1 and 6-11 determine the orientation of the upper drawer, and the entire chain determines the KC.

5.1.2.3 PKC #2

The force needed to open each drawer individually increases if the slides are not aligned as in Figure 5-6a and if the drawer body is out of square as in Figure 5-6b, but is not affected by the condition of Figure 5-6c. Figure 5-8 shows PKC #2, the alignment of four parts for each drawer - both slides and both sides that ride on the slides. Figure 5-9a shows the chains for PKC #2, which are determined separately for the two drawers with just the assumption of the drawers being located to the slides at final assembly. Chain 2L (lower) shows that the lower drawer sliding smoothness is set by the relative location of the two lower slides (links 1, 2, and 4) and the relative location of the two sides of the drawer body (a feature to feature relationship if the

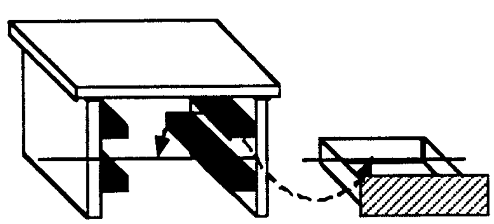


Figure 5-8. PKC #2 is determined by the alignment of both slides and the drawer slides.

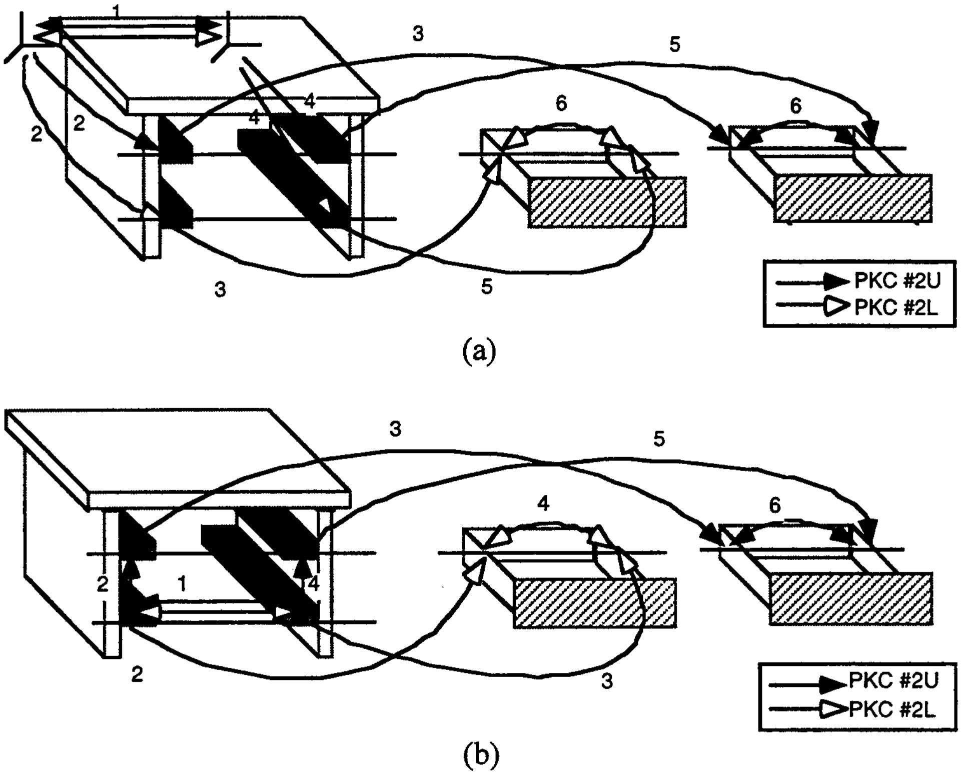


Figure 5-9. Chain that delivers PKC #2 for decomposition 1 with (a) the assumption that final assembly is accomplished by sliding the drawers onto the slides and (b) the additional assumption that the cabinet side reference frames are assigned to the lower slides. Link #1 is the root link in all cases, and lies in the cabinet frame module.

drawer is considered a complete element). Chain 2U (upper) is similar. If we make the same second assumption made for PKC #1, that the cabinet side reference frames are assigned to the lower slide, then the chains are altered as shown in Figure 5-9b. In this case chain 2L is simplified and chain 2U shows the upper drawer smoothness is affected by a more complex set of interactions that include the same link #1 from 2L, location of the two upper slides each positioned relative to the same side lower slide in the cabinet side sub-assembly, and relative position of the two sides of the drawer body when the drawer modules are assembled.

5.1.2.4 Coupling

Note the coupled nature of the KCs, which share interactions between elements and are delivered in the same elements. Specifically, both PKCs are affected by the alignment of the slides that occurs at the assembly of the cabinet frame module. The consequences of coupling include

- one misalignment can affect both KCs
- an adjustment made to correct misalignments of one KC could potentially alter the delivery of the other KC.

5.1.3 Decomposition 2: Separate Drawer Fronts.

In the second decomposition the drawer fronts are separate from the drawer body and attached at final assembly. The drawer body has an additional piece in front to which the drawer front is attached as shown in the decomposition in Figure 5-10 (as compared with the drawer body in

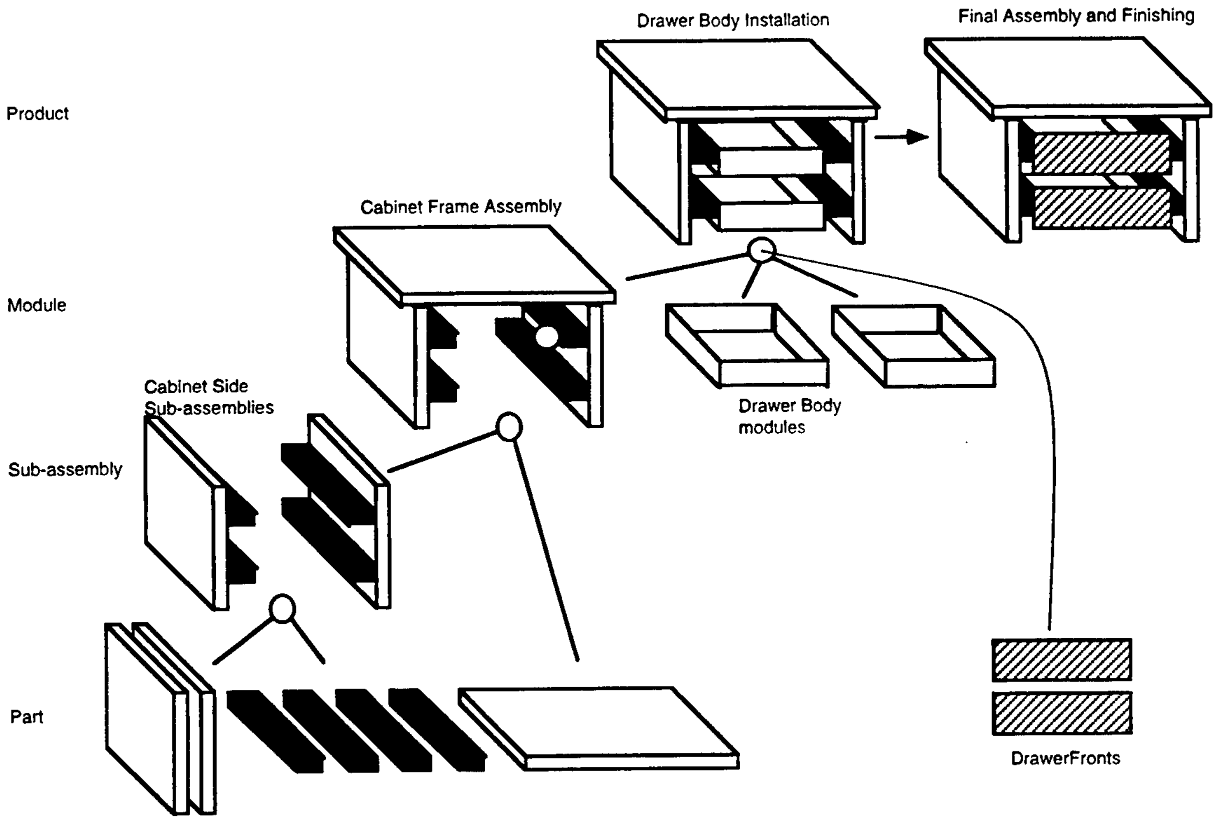


Figure 5-10. Two-drawer cabinet decomposition 2.

Figure 5-3 where the front was an integral part of the drawer body). The rest of the cabinet assembly process is the same. The drawer fronts in this case could be aligned and attached using a "spacer" after the cabinet is assembled and the drawer bodies are installed. The chain for PKC #1 (see Figure 5-11) for this case is much simpler with only three links; the position of the top drawer front to the bottom drawer front as determined by the spacer (the root link, Link #1) and the drawer edge accuracy from the point where the spacer is placed to any distance away from that point on the lower drawer edge (Link #2) and upper drawer front (Link #3). The chains for PKC #2 are the same as in decomposition 1. Note that in this decomposition the two chains are decoupled, they do not share any common links. The only way PKC #1 can be of poor quality is if the spacing operation is performed poorly or the drawer fronts have inaccurate perimeters. No other elements deliver this PKC.

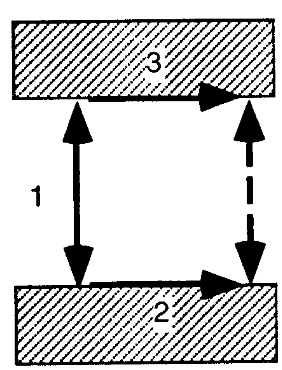


Figure 5-11. Chain that delivers PKC #1 for decomposition 2.

5.1.4 Analysis of This Example

This section analyzes this simple example by describing what the chains for each decomposition indicate about product architecture and the resulting trade-offs for design, the manufacturing approach, and the strategy. At the end of the example, a decision tree summarizes this comparison.

5.1.4.1 What the Chains Indicate About Integral Characteristics in the Product Architecture

Figure 5-12a and 5-12b show the WBS for decompositions 1 and 2, respectively. While the WBS structure is slightly different in the two cases, it does not indicate how the KCs are delivered differently. The chains in Figures 5-7 and 5-11 show that PKC #1 is delivered in several branches of the WBS in decomposition 1, but only in drawer fronts and at final assembly in decomposition 2. PKC #2 is delivered in the same way in each. A WBS representation has the weakness of distinguishing neither these similarities or differences concerning how integral characteristics, and therefore function, is delivered.

Figure 5-13 shows the mapping of KC delivery in the Hierarchy Display, with only the interactions between elements shown. The decompositions look quite different in this view.

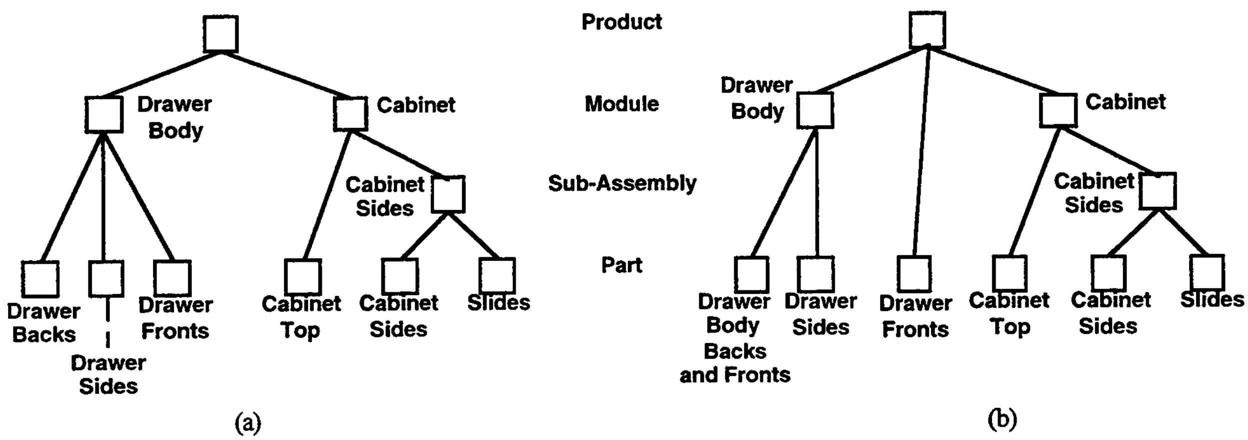


Figure 5-12. WBS for (a) decomposition 1 and (b) decomposition 2.

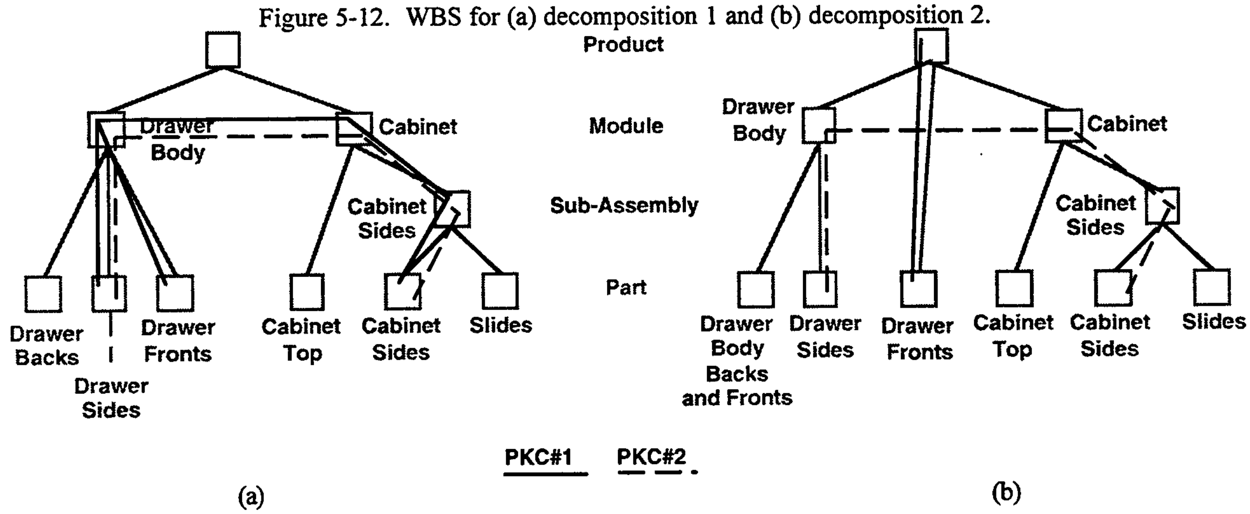


Figure 5-13. WBS with chains represented for (a) decomposition 1 and (b) decomposition 2.

Decomposition 1 (Figure 5-13a) has chains that cross the two module branches of the tree, and a high degree of coupling indicated by links for different chains between the same elements. The chains in decomposition 2 (Figure 5-13b) are less coupled (PKC #1 is decoupled from PKC #2, but both chains of PKC #2 are coupled, not shown explicitly in the figure) and PKC #1 is delivered in a smaller set of interactions.

Much about the architectural differences is revealed visually by the side-by-side comparison in Figure 5-13. Based on the metrics described in Section 4.3.1, decomposition 1 has a more integral character than decomposition 2 because its mapping of function to physical elements has greater span and it has more coupled KCs. In decomposition 2, PKC #1 is more modular in character and PKC #2 is still integral, and coupling is limited to the lower and upper drawer cases of PKC #2; this represents a mixed but more modular architecture. Decomposition 1 would score higher, i.e. more integral, in the Mapping Metric (MM) and Coupling Metric (CM).

The architectures have ramification on design and manufacturing choices. Important design parameters differ in the two designs. Decomposition 1 has an integral drawer body and front, so there is one less piece to the drawer and hence more volume in the drawer for storage. This is a simple example of an advantage on a global measure that an integral configuration typically brings. Other design issues are highlighted by chains. For example, the IPT could speculate on slide configurations where orientation of the drawer (PKC #1) and sliding force (PKC #2) could be decoupled. Knowing this is an integral characteristic of the product architecture, as indicated by the chains, the designers are motivated to find a novel design to solve this problem.

The decompositions also have different manufacturing advantages and disadvantages. Decomposition 1 has one less assembly step and reduced hand labor compared to the spacer alignment approach in decomposition 2. By pushing work into an integral sub-element, an IPT can often find ways to shorten overall assembly time, complexity, and cost. But, this comes at the expense of creating a more complex delivery of KCs. Decomposition 2 allows a standard drawer body to be used in a platform cabinet from which many styles can be made by attaching unique drawer fronts; this is an example of a strategic option available when a modular design is implemented. To implement this option in decomposition 1 would require closer coordination with the drawer assembly supplier, who would have to create a mixed line to assemble different drawer fronts to the drawer bodies.

5.1.4.2 What the Chains Reveal About Integration Risk

Section 4.3.2 described metrics for assessing the integration risk. For example, organizational boundaries that lead to integration risk associated with an integral characteristic are revealed by chains. Figures 5-14 and 5-15 repeat the architecture discussion above with a supply chain view of the example. Assume the prime designer and marketer of these cabinets assembles them and fabricates the tops and drawer fronts; this indicates that the prime prioritizes the aesthetic qualities of the product, PKC #1 and the "appearance KC".[1] One first-tier supplier (supplier

[1] For example, assume the prime has a proprietary fabrication method that allows them to create the finish on these parts that is important for the appearance KC.

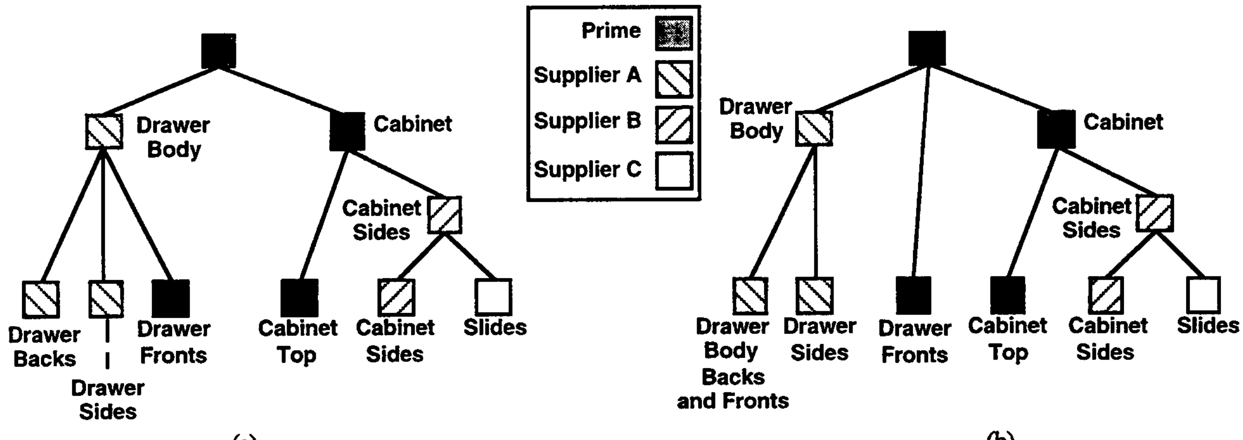


Figure 5-14. WBS with supply chain represented for (a) decomposition 1 and (b) decomposition 2. KC delivery is not clearly distinguished.

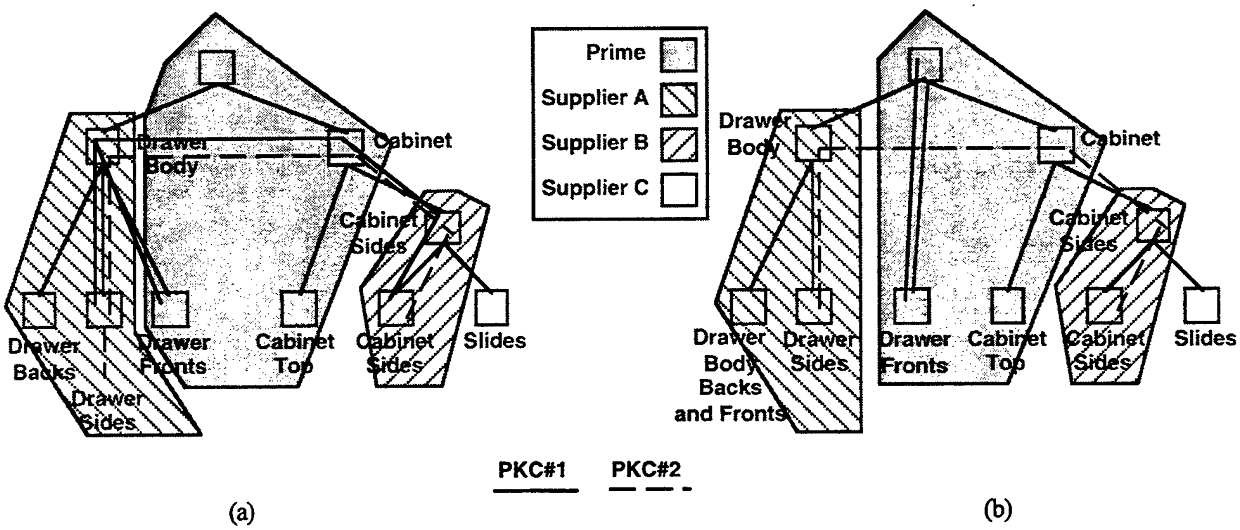


Figure 5-15. WBS with supply chain and chains represented for (a) decomposition 1 and (b) decomposition 2.

'A') makes drawer bodies[2] and a second (supplier 'B') makes the cabinet sides, but purchases the slides (supplier 'C'). The supply chain in Figure 5-14a represents decomposition 1 and that in Figure 5-14b represents decomposition 2. Note in the case of decomposition 1 that the prime ships its drawer fronts to supplier A, which assembles drawers and sends them back to the prime. In addition, many more tiers of suppliers could be included, such as fixture makers, raw material suppliers at a lower tier, etc.

Assembly of the cabinet is accomplished by the prime, whose ability to assemble a good product will be affected both by their ability to attach the parts and by the accuracy of features already in the parts, sub-assemblies, etc. The chains indicate who delivers the KCs in each decomposition. In the WBS view of Figure 5-15 interactions between elements also indicate relationships within the supply chain, indicated by links that cross from one company to another (between shaded

[2] Supplier A is a low cost supplier for this type of work that the customer "doesn't see."

areas). Section 4.3.2 describes the type of organizational boundaries that are not naturally mechanized in a tiered supply chain.

In choosing which functions it sees as core to product success, it is important for the prime to choose a supply chain strategy that is in accordance with the product decomposition and manufacturing strategy. Let us assume that the prime's strategy was to focus on PKC #1 and the appearance KC, while outsourcing responsibility for PKC #2. Judging by its selection of parts and assemblies to produce in-house, it would appear from a simple WBS and part-centric view that the prime selected the right components to properly control their KCs in either decomposition. In both cases they do control the appearance because it is modular, i.e. delivered in one operation. In decomposition 2, the prime also controls PKC #1 indicated by the line completely in the prime's shaded area, as intended. But in decomposition 1, PKC #1 is not entirely within the prime's control because the chain (the solid line in Figure 5-15a) crosses among many organizations, and it is in fact coupled to PKC #2 as discussed above. PKC #2 is shared by the prime and two suppliers, so responsibility for it is not completely outsourced and requires explicit coordination.

A similar view can be developed to examine the types of technologies that lie on chains by populating the same maps with processes represented instead of organizations to address the capability metric discussed in Section 4.3.2.

5.1.5 Summary

This example demonstrated the chain method in the context of a simple product, displayed chains in multiple views, and explored the relation of chains to a representative strategic issue (supply chain choice). Integral characteristics were found in each decomposition (summarized in Figure 5-16), and each decomposition brings with it advantages and disadvantages. If decomposition 1 is chosen, the added risk and inherent interactions of the system elements are known and will remain in focus through all phases of product development. If decomposition 2 is chosen, the rationale for accepting reduced performance and additional manufacturing cost is understood for strategic reasons.

As a final note, we see that PKC #2 is not modular in any case. Considering the concept, where the drawer slides are on two slides, it is unlikely that this KC could be made modular in any

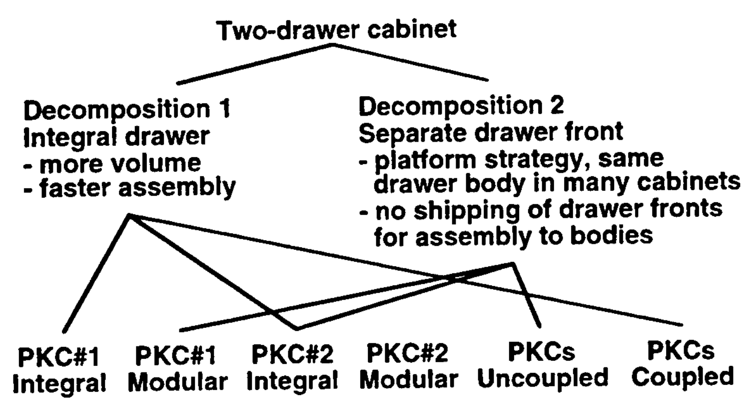


Figure 5-16. Decision tree summarizing the two-drawer chest example.

decomposition. Instead, this analysis seems to indicate that another design concept would need to be pursued if all PKCs need to be modular. This new concept will have its own PKCs that also should be subjected to the chain procedure and metrics to study the relative integrality.

5.2 Airbus 3XX Wing

This example raises issues similar to those in the C-17 example, but in this case the integral characteristic is affected by a decomposition carried over from existing products with a change in the teaming arrangement on a new product. The new teaming arrangement is driven by several issues, including logistics of shipping large assemblies from one company to another and required work share in a politically-driven partnership. The case is the yet-to-be designed Airbus 3XX, a new 600 seat aircraft that will enter Airbus into a new segment of the commercial airline market. Chains are incorporated into this example to portray the degree of integration risk associated with the new teaming arrangement.

5.2.1 Product Description and Business Context

Airbus is a consortium of four independent aerospace companies in four different European countries: Aerospatiale in France, Daimler-Benz in Germany, British Aerospace (BAe) in England, and CASA in Spain. While these companies all have their own products, together as Airbus they build a fleet of commercial transport aircraft. This case focuses specifically on the wings built by BAe and aircraft final assembled at either Aerospatiale or Daimler-Benz.

5.2.1.1 Wing Description and Decomposition

Wing design is among the most complex design and manufacturing activities in the airframe [Niu] and is the structural assembly where dimensional control appears to be most critical.[3] BAe builds the wings for all Airbus aircraft and will be responsible for them on the 3XX. Every wing in Airbus aircraft has a similar layout of the major structural members. Figure 5-17 shows the

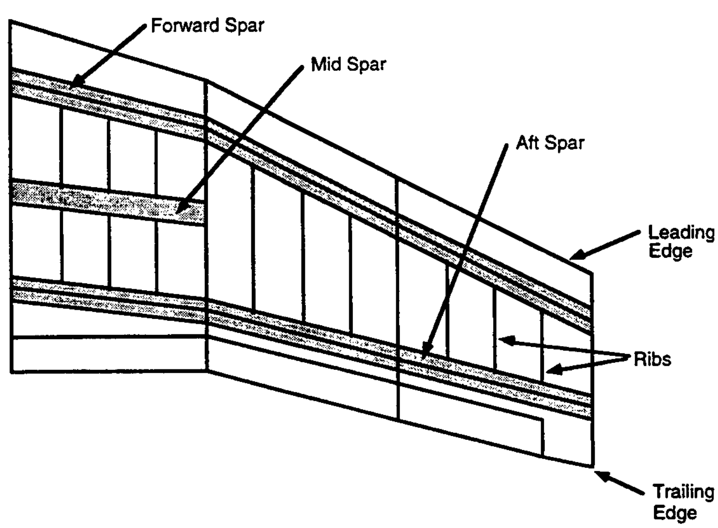


Figure 5-17. Layout of typical Airbus wing (top view, top skin removed).

[3] It is worth noting here that Boeing, the world leader in commercial aircraft, has outsourced vast amounts of aircraft design, fabrication, and assembly, but not wings. Boeing has clearly identified wings as one of the core parts of their business.

layout of the wing. There are three spars marked in Figure 5-17 that run the full or partial length of the wing and are the major load carrying elements. Spars are beams that transfer most of the differential and torsional loads from the wing structure into the aircraft fuselage. This discussion focuses on the forward and aft spars. The case study in Section 5.4 focuses on a similar wing-like assembly and describes similar parts in more detail.

The wing of the Airbus 340, the consortium's largest aircraft, has the decomposition shown in Figure 5-18. In this decomposition, the forward and aft spars are segmented into three major sections. It is reasonable to expect that Airbus has built up tremendous corporate knowledge and experience tailored to this decomposition, including wing design methods, tooling design, time studies and other predictive analyses, fastening and fabrication equipment, etc. For these reasons it would be desirable to utilize this decomposition in new products as well. The 3XX is larger than the 340, so relevant knowledge would be carried forward from the 340 to the 3XX by maintaining this decomposition.

The final assembly of all wings currently is accomplished in England and then the wings are loaded into specialized large aircraft to be flown to Germany or France, depending on the model, for final assembly of the aircraft. In the 3XX case the size of the wing will exceed the size of the transport aircraft, and no overland (or Chunnel) option is possible. Simply put, the wings of the airplane, which grow in greater proportion than the fuselage when all other things are equal, have "outgrown the decomposition". The results of this limitation are described below. Figure 5-19 shows a direct application of the current decomposition to the 3XX problem that overcomes the logistics limitations. In this candidate decomposition, the wing would be segmented into three wing box sub-assemblies like the 340 outboard sub-assembly. The three large sub-assemblies would then be shipped for final assembly. This candidate will be pursued in the analysis below.

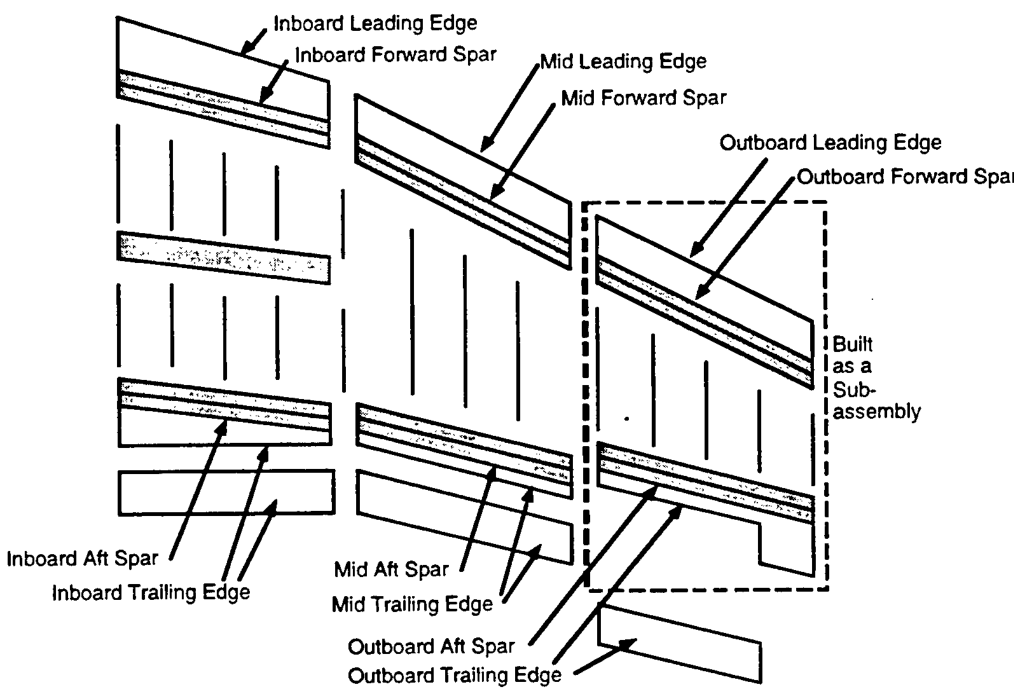


Figure 5-18. Decomposition of the Airbus 340 wing.

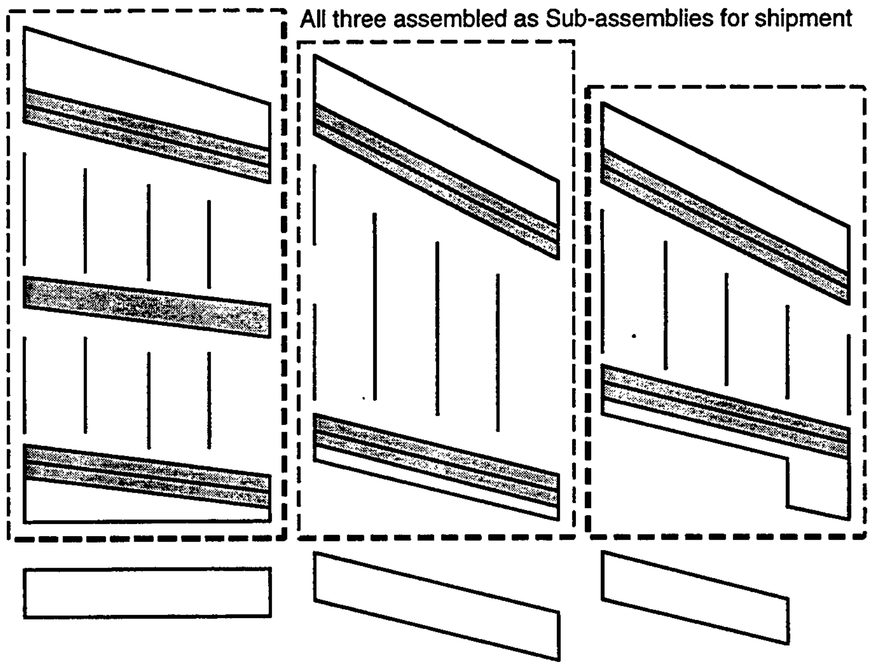


Figure 5-19. Decomposition of the Airbus 3XX wing that follows the existing decomposition but completes more work prior to final assembly.

5.2.1.2 Business Context

5.2.1.2.1 Sales Volume and Relation to Other and New Versions

Airbus has been increasing its market share and has the stated goal of attaining equal status with Boeing in international commercial aircraft sales. The 3XX is intended to enter a market currently monopolized by the Boeing 747. Success in this market is critical to Airbus, and design of the new aircraft represents a likely investment of billions of US dollars. This is stated in cursory fashion just to emphasize the point that this isn't a research or experimentation activity, but a significant product development project where early identification of risks and mitigation plans to overcome the risks are central elements of success. Chains can be used to support this analysis. This simple portrayal of this complex example illustrates how chains are a central coordination framework for IPD because they indicate integration issues and allow for structured recognition of integration risks in concept design.

5.2.1.2.2 Teaming Arrangement

As described above, BAe designs and builds the wings while another company on the European continent is the likely final designer and assembler for the 3XX. Airbus teaming arrangements are tightly controlled by work content agreements among the consortium members that set the percentage of all labor each company's employees must perform and material that they must provide. This limits the flexibility of redefining roles for the different companies. For this reason domestic employees at the final assembler will perform all the labor in those plants; i.e. BAe can not send their own experienced employees to do similar work at the designated final assembly plant. This fact, combined with the logistics limitation that requires final assembly of these large wings be at the aircraft final assembly plant, requires that a different company with its own

employees will perform wing final assembly work on the 3XX that is traditionally performed by BAe.

5.2.1.2.3 Strategies and Issues

Airbus, like all major aerospace entities, is undergoing a transition in manufacturing to reduce cost by implementing tenets of lean manufacturing, focusing on improving quality, and improving assembly efficiency. In order to compete with Boeing, who itself has highly ambitious cost and assembly cycle time reduction initiatives (see Section 5.4), all components of Airbus are attempting to become more efficient in manufacturing and assembly.[4] This presents some competing challenges. Overall quality of the product has to be at a highly competitive level, and at the same time the dimensional control activities that are currently relied on to deliver quality but make assembly so inefficient have to be rationalized. So at the same time the wing final assembly work will be moving from one company to another, it has to be made simpler and more efficient.[5]

5.2.2 Insight Into Architectural Complexity

The change in teaming arrangement due to the logistics constraints changes which organizations are responsible for integral characteristics of the wing. The following shows that if we attempt to use the candidate decomposition that follows from the existing decomposition, we find increased integration risk.

5.2.2.1 Key Performance Parameter and Key Characteristic

In this example I investigate one KPP and two KCs. The KPP is the carriage of the differential and torsional loads on the wing. The associated KCs are the proper alignment of the major lateral load carrying elements - the spars. While there are certainly numerous other KCs in a wing, this example will focus only on these closely related KCs simply to illustrate the impact that the organizational and logistics constraints will have on these integral characteristics.

5.2.2.2 Chains for Spar Alignment

There are two PKCs for each KC that are the same in the existing 340 decomposition and in the candidate for the 3XX shown in Figure 5-19. The two for the forward spar are (with those for the aft spar being equivalent):

PKC #1: alignment of the outboard edge of the Inboard Forward Spar with the inboard edge of the Mid Forward Spar
PKC #2: alignment of the outboard edge of the Mid Forward Spar with the inboard edge of the Outboard Forward Spar

Figure 5-20a shows the PKCs for the Forward and Aft Spars. Reference frames are depicted in the decomposition for each leading edge component (6 in all), and one for the outboard wing section sub-assembly that is shipped as a complete unit to final assembly. Figure 5-20b shows

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[4] BAe has a program called Leanwing whose intent is to identify applicable lean manufacturing principles to wing design and production, similar in intent to the U.S. Lean Aircraft Initiative.
[5] A more complete discussion of this type of trade-off is included in the case studies of Section 5-4 and Chapter 7.

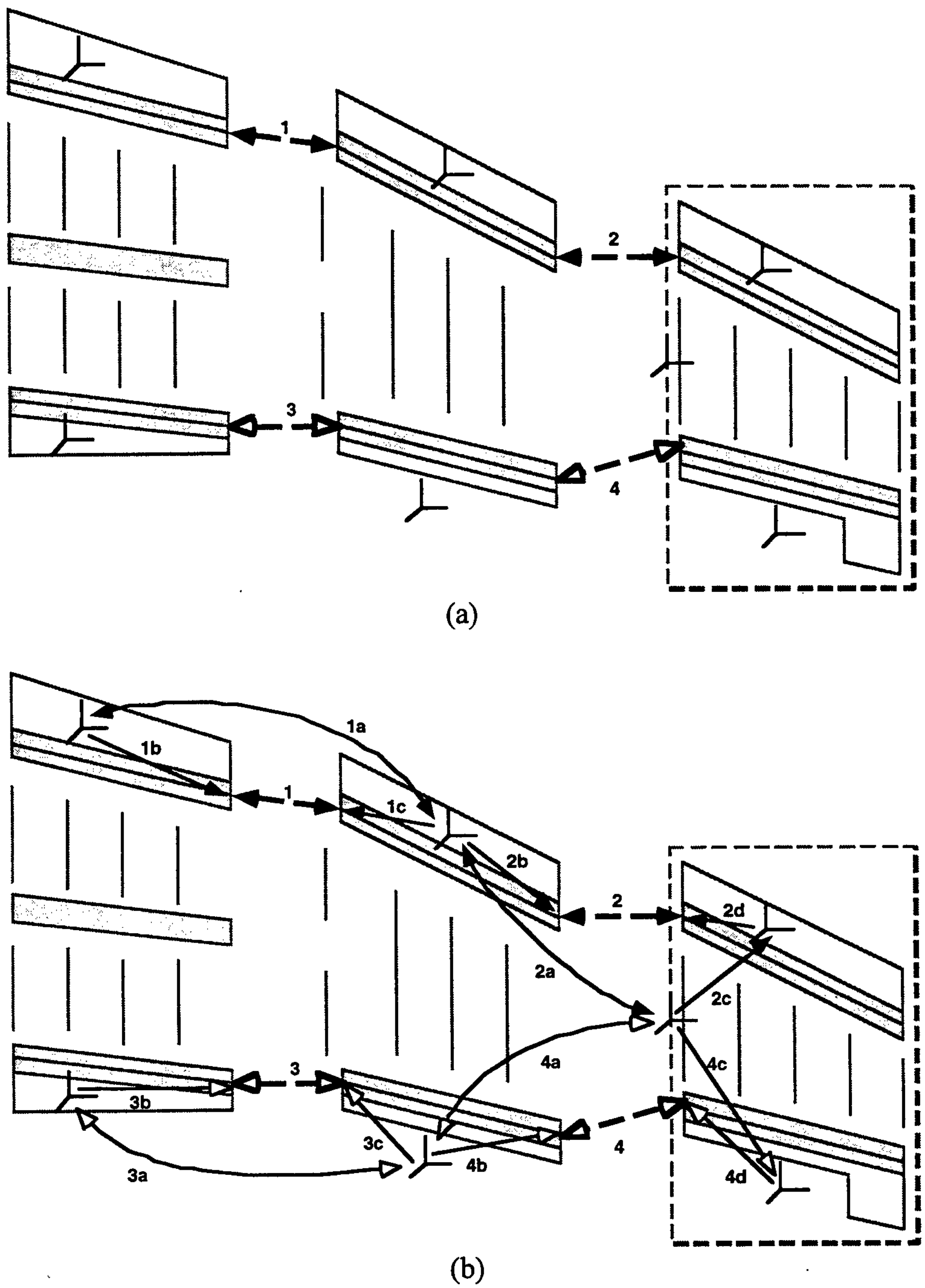


Figure 5-20. (a) PKCs for the 340 and 3XX, (b) the chains for the PKCs in the existing decomposition.

the chains for the existing decomposition, with the links numbered a, b, c, etc. Note that the additional reference frame in the outboard sub-assembly creates an additional reference frame whose relationship with the component reference frame adds an extra link in the chains for PKCs #2 and #4. The chains are decoupled, however, because they do not share the same interactions

between two elements (there are no common links between reference frames.[6]

Figure 5-21a shows the chains in the candidate decomposition for the 3XX. Now reference frames are present in the two new sub-assemblies, which add two links to the chains of PKCs #1 and #3 and one new link to the other two chains. In addition, PKCs #1 and #3 are now coupled due to the common interaction between the inboard and center sub-assemblies, and PKCs #2 and #4 four are also coupled. This means that in each sub-assembly, an AKC must be delivered that positions the forward and aft spars relative to each other in the fore/aft direction, as shown in Figure 5-21b. The slight change in decomposition, from one sub-assembly and four components to three sub-assemblies altered the chains and the coupling of chains.

5.2.2.3 Analysis of the Architectural Complexity

The chains in Figures 5-20 and 5-21a indicate that these are moderately integral characteristics; they are delivered in one module (one wing) but are delivered at the height of sub-assemblies. Following the chain structure metrics described, we can analyze the architectural impact of the decomposition change:

1. The MM score for these KCs remains the same because they still span sub-assemblies.
2. The chains are coupled in the sub-assemblies; that is, at final wing assembly the two spar alignments between the inboard and mid sub-assemblies can not be achieved independently. The CM score is now higher.

Because of the coupled integrality, we declare these to be integral characteristics that should be assessed for their integration risk. Scoring in terms of all three risk metrics are altered by this

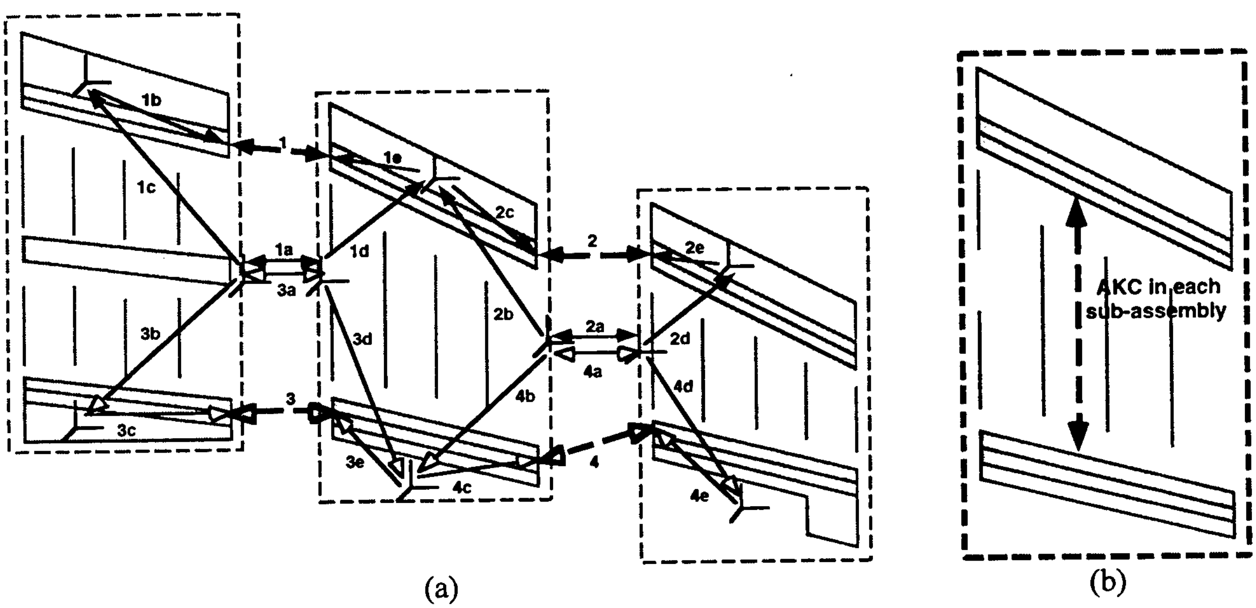


Figure 5-21. (a) Chains for the PKCs in the new candidate decomposition, and (b) an AKC in each sub-assembly required to achieve the coupled PKCs.

[6] Also note that at this point we are addressing this problem at a very high level that these graphical chains support. We do not have to consider that there are in fact links between each spar to the reference frame of its leading edge component. These links would complicate the view but not add any information to the first level decomposition analysis.

decomposition and teaming arrangement:

1. There are more elements in each chain due to the additional sub-assembly step.
2. There is an important organizational boundary in the chains with the root link delivered at final assembly by a different company; and, different sub-assemblies would be candidates to be made by different companies within BAe.
3. The delivery of the PKCs at final assembly is subject to an unproven process. Specifically, the joining of the three spar sections will take place in a different plant with new workers and on untested equipment, that at the same time is required to make the process more efficient.

The simple example demonstrates the utility of the systematic method for identifying chains and assessing them with a structured set of metrics. BAe of course recognizes this basic issue and has plans for deploying teams to interact with the new assembly line workers and perform needed corrective actions. This will be a critical issue in production ramp up that will affect overall cost, assembly cycle time, and quality that will challenge the companies' ability to communicate about new issues. The specific issues indicated by chains, coupling and increased integration risk, reinforce the importance of this issue. Chains contribute to the type of dialogue that must occur for this source of risk to be mitigated successfully. More importantly, by addressing the problem systematically, non-obvious issues are more likely to be found, especially in an environment where the product or architecture is changing significantly.

5.3 Ford Light Truck

This example shows two candidate physical decompositions of light truck bodies and discusses the competing priorities of KC delivery and manufacturing, technology, and platform strategy.

5.3.1 Product Description and Business Context

Ford Motor Company Light Truck division builds several products: large and small sport utility vehicles (SUVs), large and small pickup trucks each with many body styles, and two minivans also with different body styles. They are built in a variety of plants in many geographic regions, and some plants assemble more than one vehicle and a variety of vehicle types. An all new version of a vehicle is launched approximately every 10 years, and goes through a major refresh every 4 or 5 years (once or twice between new versions). In addition, completely new products are launched often in this group of products. In recent years the SUV market has increased from just the so-called "small" competitors (Ford Explorer, Toyota 4Runner, Jeep Grand Cherokee, etc.) to both large SUVs (Ford Expedition, Chevrolet Tahoe) and mini SUVs (Toyota Rav4). Also, luxury models of these vehicles have been introduced. A major tenet of the lean paradigm was the competitive advantage attained in being able to launch new versions and all new vehicles quickly to meet shifting customer demands, as exhibited in light trucks during the 1990s.

From the perspective of KC delivery, the issues are quality and economy. The light truck market is highly dynamic and competitive in terms of model mix, quality, and price, so the consistent delivery of KCs within the context of a lean production system is a must if the product is be competitive. From the perspective of manufacturing strategy, a significant issue is the amount that must be invested to convert an existing production plant to a new model. Investments in

new assembly equipment for new models are kept to a minimum and are heavily debated; assembly lines cost several hundred million dollars. From a technology strategy, new advances in body stamping technology allow for much larger stampings than ever before (as described below). This advance in fabrication technology allows for a reduction in assembly. Finally, the advantages of a platform strategy include the ability to shift production of vehicles around among different plants, and to quickly develop new models based on existing platforms, by having all (or several) vehicles based on a common architecture. This allows for the introduction of new models in existing plants and to increase production of one product that is selling large numbers by building them at plants that produce a vehicle whose demand is sagging, instead of running one plant overtime or at maximum capacity and laying off workers at the other.

5.3.1.1 Two Candidate Light Truck Body Decompositions

Figure 5-22a shows some basic terminology depicted on schematics of light truck bodies. The A-pillar is located at the front of the front door, the B-pillar is located between the two doors, and the C-pillar is located between the door and quarter panel. Figure 5-22b shows the terminology for pickup trucks, with the cab and bed indicated.

Two candidate decompositions of a vehicle are in stark contrast. Figure 5-22 shows decomposition 1, which has a single side aperture stampings for SUVs and pickups. A single side aperture stamping is a single part with a few welded reinforcements for strength that includes both exterior and interior surfaces. Figure 5-23a shows a schematic of a stamping for each type of vehicle, and Figure F-23b shows decomposition 1 applied to a pickup truck. The decomposition has two side stampings, fenders and a hood forward, a floor, a top, and other elements enclosing the cab and bed. Exterior surfaces require much better finish, so incorporating both exterior and interior surfaces, and integrating the size of the part, into a single stamping represents a significant technology enhancement in body panel fabrication.

An alternative is a more traditional approach that will be called decomposition 2. Figure 5-24a shows the decomposition of a SUV into several modules. Figure 5-24b shows the decomposition of a pickup into bed and cab modules.

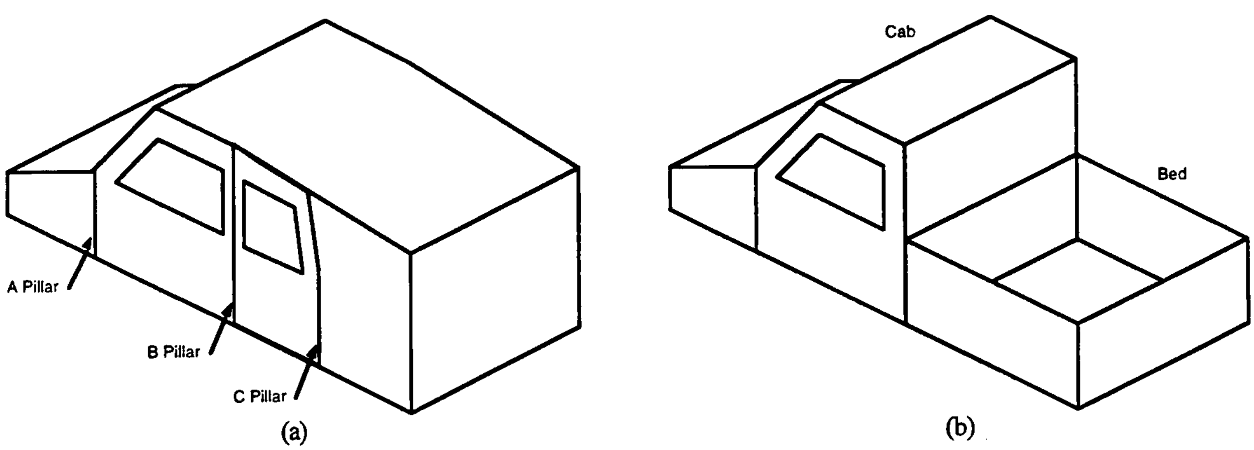


Figure 5-22. Terminology of light truck bodies.

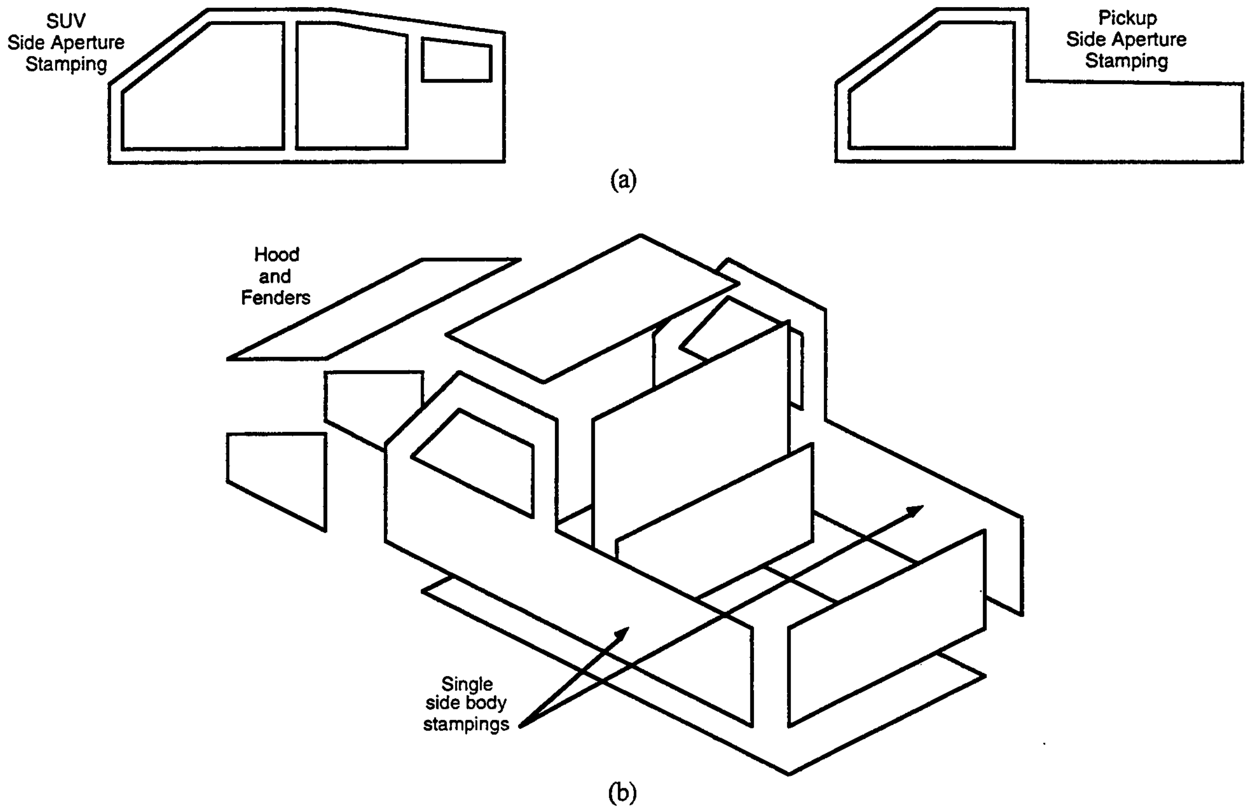


Figure 5-23. (a) Schematic of SUV and pickup single side aperture stampings, and (b) decomposition 1 for a pickup.

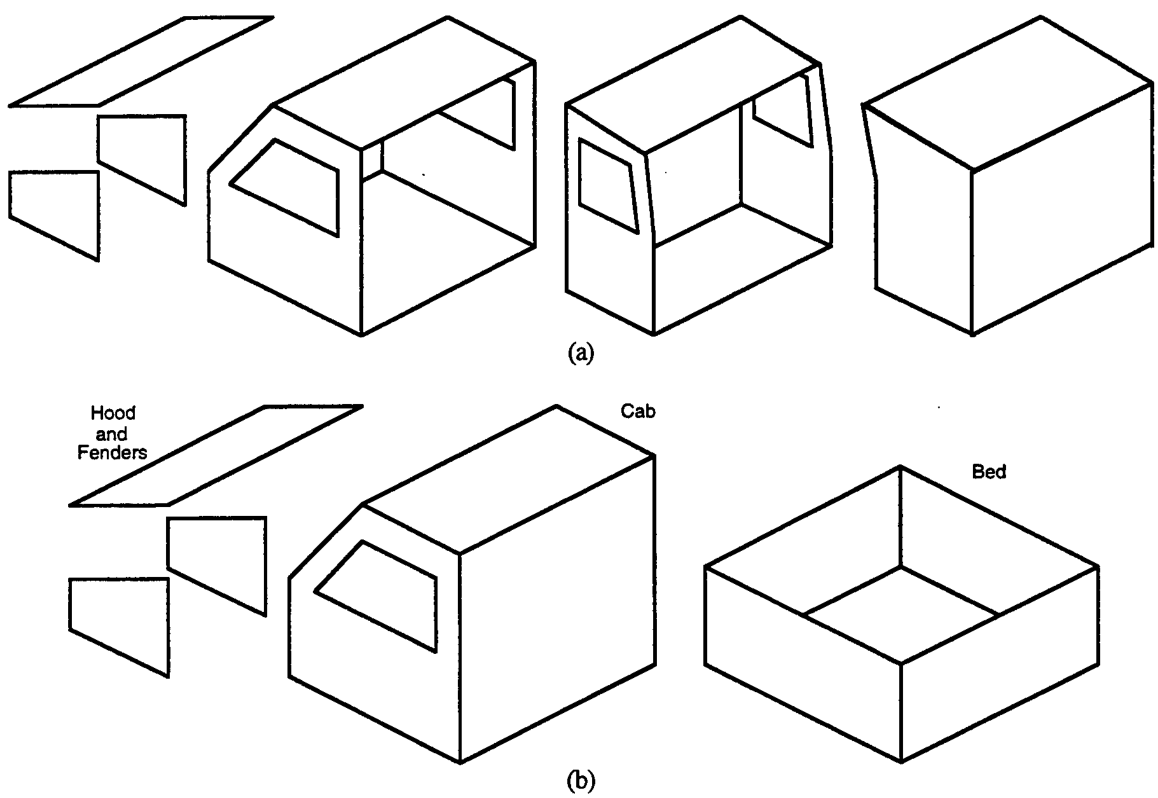


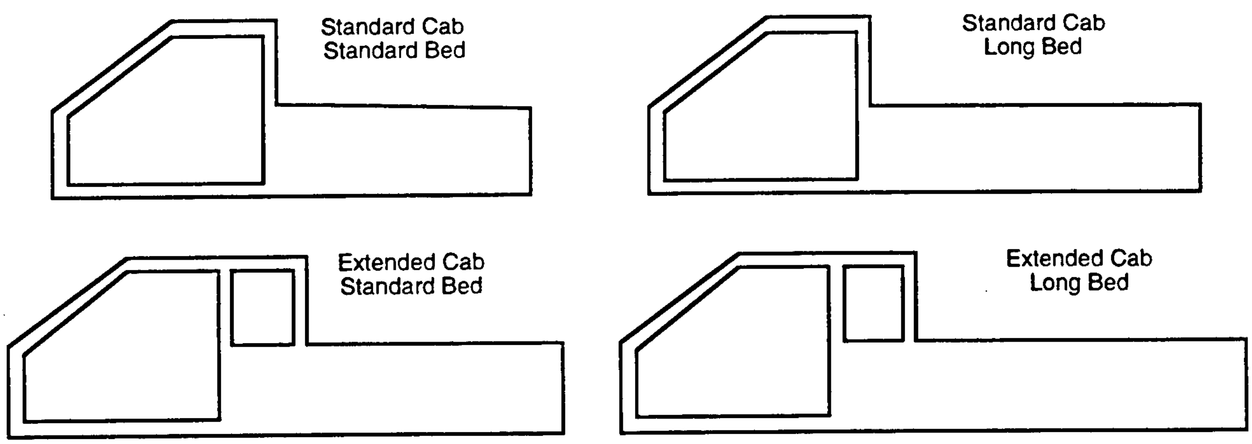
Figure 5-24. Decomposition 2 of a (a) SUV and (b) pickup.

Model variations in pickups point out trade-offs among these two options. A pickup may come with two varieties of cabs and two bed lengths, leading to four vehicle types. As shown in Figure 5-25a, four full stampings are required to create the four models in decomposition 1. In decomposition 2, shown in Figure 5-25b, there are two cab stampings and two bed stampings, any of which may be combined to make the four models. The latter case has four smaller stampings and greater flexibility. A similar discussion can be conducted for minivans and some SUVs, where models come in a small and large version.

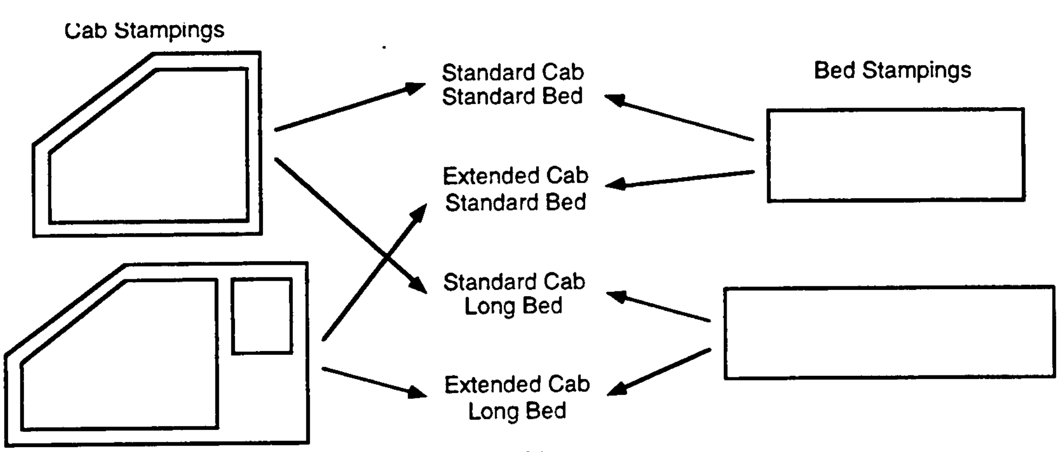
5.3.1.2 Business Context Trade-offs

The challenge is to pick a single decomposition, say from among the two choices described above, and best satisfy the demands of KC delivery and three strategic issues related to the full line of light trucks.

The three strategy issues do not indicate a clearly superior choice. From the manufacturing strategy perspective, achieving a single architecture will require conversion of many plants because the current portfolio of products is built in a mix of the two decompositions. Large investments would be required to make the conversion to either candidate. The main question is



(a)



(b)

Figure 5-25. Model variations associated with the two decomposition options.

which decomposition would require more investment? There is no obvious answer to that question. From the technology strategy perspective, decomposition 1 exploits a new technology that enables the company to simplify assembly. This indicates an advantage for decomposition 1. From the platform strategy perspective, either option has the potential to achieve the flexibility. Each option faces fundamental limitations in the variety of vehicle lengths (decomposition 1) or vehicle widths (decomposition 2) of the single architecture group that could all be assembled on the same line. The stampings associated with decomposition 2 are smaller and can be combined into the four combinations of truck bodies, indicating an advantage for decomposition 2.

5.3.2 Dimensional Control Approach

The fourth consideration, KC delivery, must also be considered in the debate with the three strategic issues. This section describes an example KC, and explains how KC deliverability investigated with chains could perhaps be used to break the tie. Ford is in a position to exploit quantitative variation analysis at a very early stage in the debate to further enhance this approach.

5.3.2.1 Key Performance Parameters, Key Characteristics, and an Example PKC and Chain

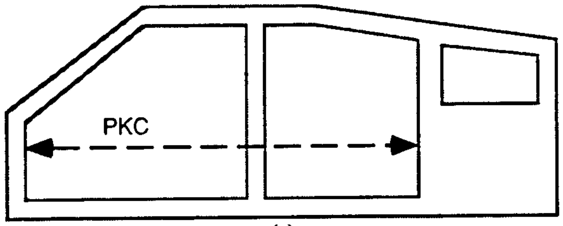
The region between the A and C pillars in minivans and SUVs, and between the A and B pillars in pickups and two-door vehicles, involves several KPPs. One type achieves customer satisfaction with the exterior look via well proportioned boundaries around the doors. The second achieves customer comfort in the interior via the proper fit up of doors to the body, which seals the interior from the outside air temperature, noise, moisture, etc. These Key Performance Parameters (KPPs) result in two major types of KCs involving the margins around the doors, and the proper fit of the doors against the structure. Finally, these KCs spawn several PKCs, specific dimensions that affect the margins, or the fit of the doors, etc.

Let us consider one of these PKCs, the distance fore to aft from the A pillar to the forward edge of the quarter panel at the C pillar. Figure 5-26a shows the PKC. Note that in decomposition 1 the PKC is fully delivered in the stamping. Figure 5-26b shows the chain for decomposition 2. The chain spans two major modules of the car body so that the final body assembly is the root element.

Two of the three integrality metrics can be applied: the mapping metric and the critical path metric. Decomposition 1 is superior in each case; the PKC is delivered in a single (albeit complex) part and therefore is completely off the assembly critical path. In decomposition 2, the PKC is delivered in two modules and far down the assembly line where it is likely to lie on the critical path. A full analysis of this and several other PKCs has the opportunity to reveal the integral characteristics and integration risks of each decomposition.

5.3.2.2 Ability to Move Directly to Quantitative Analysis

Ford Motor Company Body and Assembly Operations is an ardent user of quantitative variation



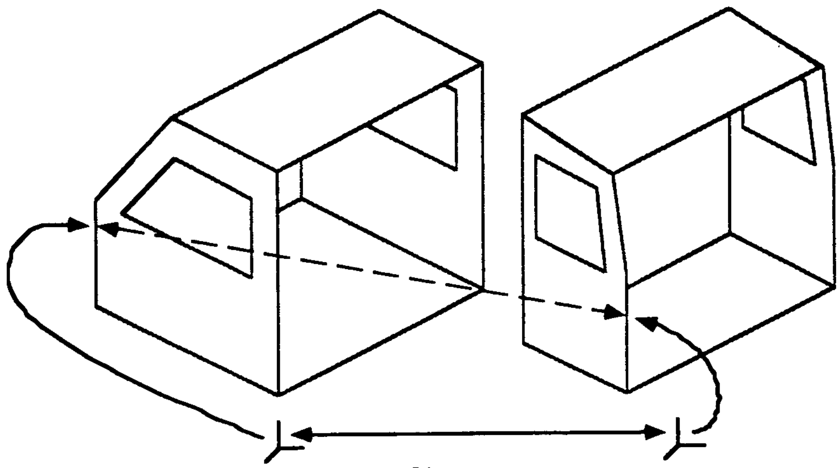


Figure 5-26. (a) PKC from the A pillar to quarter panel edge at C pillar, and (b) chain for balloon build option.

analysis, specifically Variation Simulation Analysis (VSA) [Sweder and Pollack].[7] It is valuable to compare the environment of Ford's VSA use to the general case described in Section 4.5. Based on a wealth of existing information, Ford exploits quantitative variation analysis sooner than can generally be achieved in new designs in other industries.

The key to Ford's ability to use VSA analysis is the existence of a "generic" set of locators and measurement points used on all parts of a particular vehicle family. These generics serve as the starting point in all new vehicles though they will be tailored somewhat in each application. Ford also uses existing technologies or extensions of well established technologies in all new vehicle developments. Automotive production happens so rapidly and is so reliable that new technologies enter the process only after a great deal of maturity. For this reason, analogous or precise process capability data is available early in design, perhaps from the exact suppliers that will be involved in a new product. This also includes assembly fixturing and tooling concepts in body shops, which are chosen for a particular line from a variety of common or evolutionary capabilities.

With generic locating and measurement schemes and existing capability data, Ford can avoid creating this information just for the use of VSA. This data is readily available to be incorporated with early design concepts or higher level architectural trade-offs like that described here. For this reason, at least in theory if not in practice, Ford has at its disposal all that is required to make VSA a consistent piece of an iterative concept design process.

[7] Sweder and Pollack have published a paper explaining how Ford uses VSA, I have also had several personal discussions with Ford on the subject.

New designs in other industries can not be assumed to have at their disposal generic locating and measurement schemes, firm process capability data, and perhaps not even an established assembly technique. For this reason the Ford model is not immediately transportable to all development activities, though Ford's ability to move to quantitative analysis sooner is a worthy goal.

5.3.3 Ford Example Conclusions

In this example, a high-level architecture decision was not firmly supported one way or the other by the strategy considerations alone. The chain analysis showed a difference in the architecture of the two processes in terms of this one KC. In addition, I briefly described how, with the right information available, a quantitative analysis of variation is possible and according to Sweder and Pollack, has been used previously in early design tradeoffs. This example extended concepts of architecture and strategy tradeoffs beyond the aircraft examples, and again was supported by chain representations of KC delivery.

5.4 767 Horizontal Stabilizer

The final example involves aspects of a case study that our project team performed at Vought Aircraft Company[8] in 1995, where we set out to formulate a set of tools based around chains and tested on a real design problem. The problem considered was an assembly process redesign for a family of large skin panel sub-assemblies that are fabricated and assembled by Vought. Vought builds such sub-assemblies for a variety of Boeing products and had other existing and potential new business that were potential candidates for the new process. The Boeing 767 horizontal stabilizer is described in this section in detail. The goal of the new process was to achieve the dimensional relationships among the parts while eliminating the fixtures by changing the approach to one where the parts contain most or all of their mating features. The change was intended to allow Vought to become more flexible in its assembly process. This is an example of a producibility and technology strategy that, as in the other cases, is better suited to modular products and therefore sensitive to integrality and integration risk.

This example makes two contributions: it describes decomposition tradeoffs in the context of a larger group of KCs, and shows how quantitative analysis is structured by the results of the chain procedure. Note that this is an example where all parts of the assembly are known; i.e. the design and decomposition were complete at the time of the study. Our investigation here considers different decompositions of the product and does not require all the available information about the actual parts. Then selected detailed information is used for the quantitative analysis. While this does not precisely reflect the context of concept design, the example proves a larger point about what can and must be accomplished during concept design in order for an IPT to control the architecture of the product.

This section describes the product, a decomposition trade-off of the product, and a quantitative variation analysis of one of the candidate processes for the 767 upper skin.

[8] I will refer to the company as Vought, though they were purchased in 1995 by Northrop-Grumman and were then known as the Vought Center of the Northrop-Grumman Commercial Aircraft Division (and recently Northrop-Grumman was purchased by Lockheed Martin).

5.4.1 Product Description and Business Context

This section describes the horizontal stabilizer, introducing the functionality, physical layout, and the decomposition into sub-assemblies and parts. In addition, business strategies that influence the process choice are discussed, including its relation to other Boeing commercial aircraft models, supply chain and outsourcing strategy, and a move toward flexibility in the assembly process.

5.4.1.1 The 767 Horizontal Stabilizer

The Horizontal Stabilizer is located at the aft end of the aircraft (see Figure 5-27), enabling the aircraft to climb and descend by pivoting down or up to direct airflow, and balancing the moments of the aircraft. The principal requirements for this structure are to carry to the aerodynamic loads while minimizing the drag it creates so overall system efficiency is maximized. The assembly is built in three main modules: left and right stabilizers and a center box (see Figure 5-28). The entire stabilizer in this case study pivots about its long axis as a solid unit on two points, one at the aft end of each stabilizer, by the motion of an actuator that moves the front of the center box up and down (see Figure 5-28).

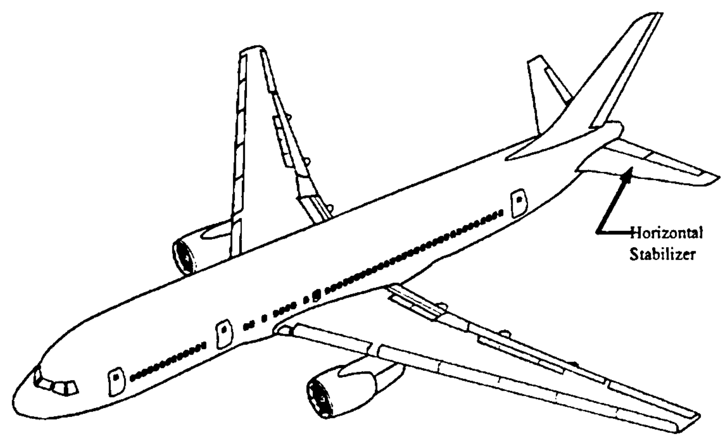


Figure 5-27. Horizontal Stabilizer position on the aircraft.

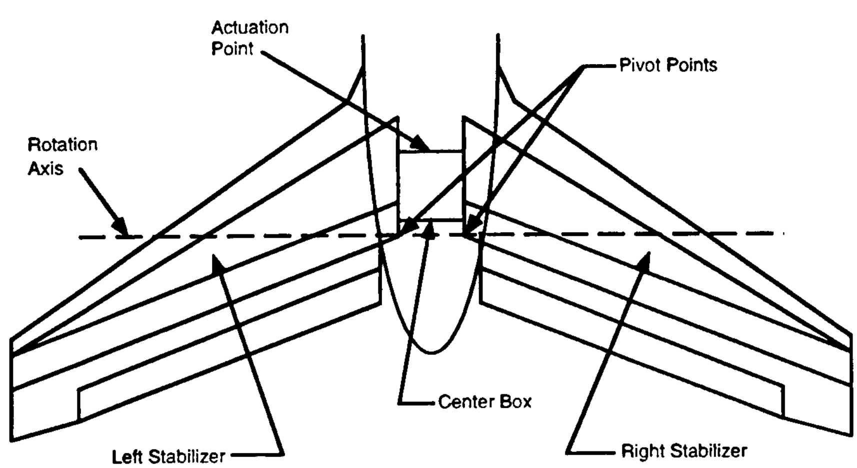


Figure 5-28. Three modules of the Horizontal Stabilizer, the axis of rotation, and the actuation and pivot points.

Each left or right stabilizer[9] is in effect a box beam structure (called the main torque box) with a forward and aft spar running the full length, stiffened upper and lower skins that act as the top and bottom of the box, several ribs along the length, and a heavy inboard structure that connects the spars, the inner-most rib, and the upper and lower skins, as shown in Figure 5-29a (without the upper skin). Figure 5-29b shows the configuration of the inboard structure that includes a forward and aft "end fitting" and an upper and lower "plus chord" (described further below). The main torque box sustains the bulk of the differential loads on the upper and lower surfaces and torsion loads along the length of the stabilizer. The section forward of the main torque box carries some loads also but mainly creates an aerodynamic shape, while the section aft completes the airfoil shape and includes the hinged section called the elevator whose position can be adjusted to change the airfoil shape

5.4.1.1.1 Decomposition

Figure 5-30 shows an exploded view of the right stabilizer as it is currently decomposed. There are four sub-assemblies:

- Forward Torque Box (FTB), including the *forward spar and end fitting*
- Fixed Trailing Edge (FTE), including the *aft spar and end fitting*
- Upper Skin, including the *upper plus chord*
- Lower Skin, including the *lower plus chord*

The ribs, each installed individually, as a group are considered as a fifth sub-assembly in this analysis.

Figure 5-31 shows a WBS, including the detail parts that are part of the discussion below. The fourth layer of the decomposition is a group of parts and components; the spars and ribs are

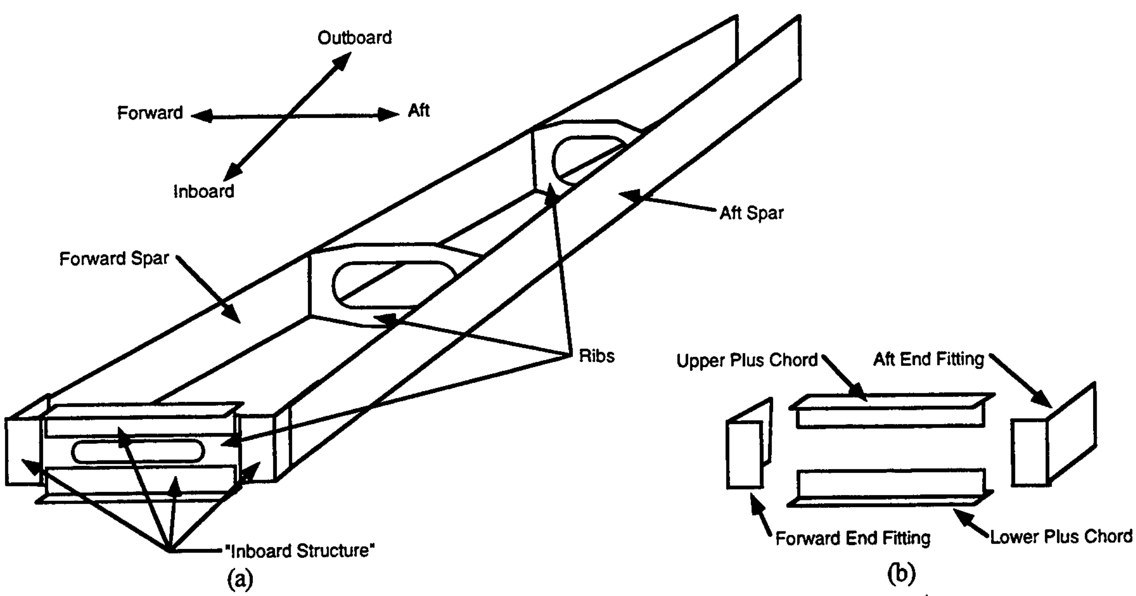


Figure 5-29. The two spars, ribs, and the "inboard structure" - detailed in (b) - make up the main torque box along with the upper and lower skins that are not shown here.

[9] From this point forward I will explain the product in terms of the right stabilizer; the left is symmetric.

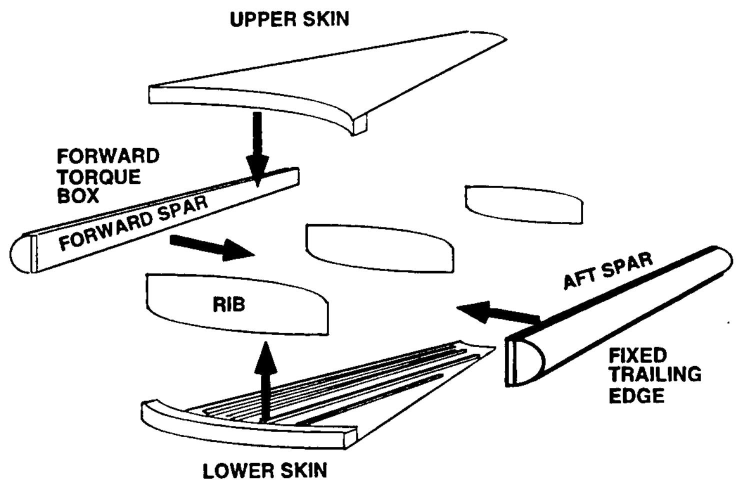


Figure 5-30. Exploded view of sub-assemblies making up the right horizontal stabilizer.

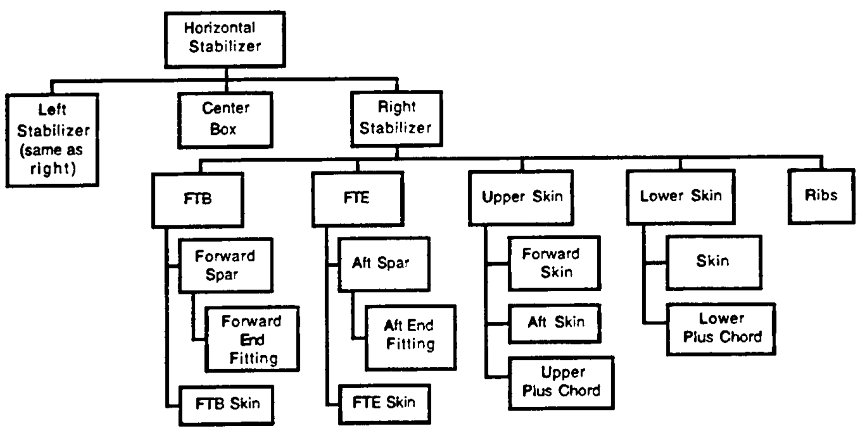


Figure 5-31. Horizontal Stabilizer WBS of the current decomposition.

themselves assemblies of a few parts so they are "components." Note that the main torque box is not built as a sub-assembly, but is parsed out to the five sub-assemblies and is completed when these five-sub-assemblies are assembled as a module. The assembly process itself is described further in the next section.

The sub-assembly detailed at the end of this example is the upper skin of the right stabilizer, which forms the top of the main torque box. The upper and lower skins are similar with the upper skin being slightly more complex. Figure 5-32 shows the upper skin. This assembly is approximately 40 feet long and 6 feet wide. It is built of the following parts, all of which are machined aluminum and shot peened[10] to improve corrosion and fatigue crack resistance:

- Forward Skin - a long sheet of varying thickness that carries compressive and tensile loads and forms the aerodynamic surface.
- Aft Skin - similar to the forward skin; the aft skin acts as an access panel during assembly.

[10] The shot peen process distorts the shape of parts after machining, with the most significant distortion being growth on the order of 0.0001 inch of growth per inch of length. This is a significant source of variation, and is common to all parts of this type in aircraft. Over the 40ft length, for example, shot peen growth is on the order of 1mm.

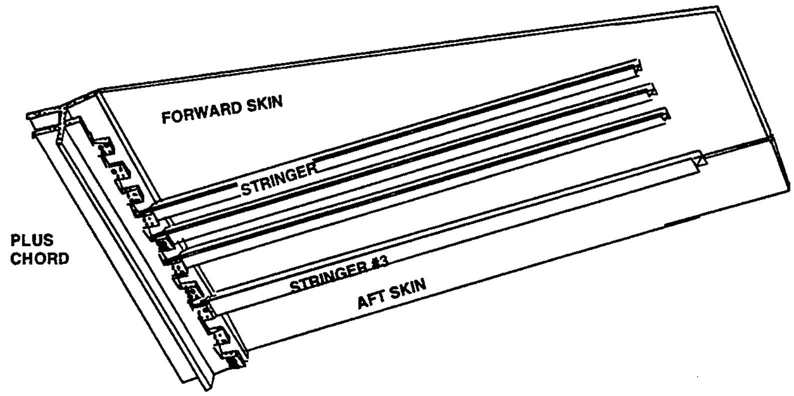


Figure 5-32. Skin assembly shown from the lower view. Note, this is a left upper skin; the right upper skin is symmetric.

- Stringers - long, slender beams that serve to stiffen the skins, with Z, I, or J cross-sections along the full length that minimize weight and maximize stiffness. They are riveted directly to the skin and fastened to the plus chord. Stringer #3 serves as a splice between the two skins (visible in Figure 5-32), while the other stringers are fastened to just one of the skins.
- Plus Chord - a heavy heat-treated, machined extrusion that forms the top of the inboard structure (shown in Figure 5-29b) at the root of the main torque box, where maximum loads in the stabilizer are absorbed. The complex geometry and intricate processing steps make the final shape of the plus chord difficult to control. This part aligns with the two end fittings to provide the inboard structural strength.

5.4.1.2 Strategic Objectives Derived from the Business Context

The strategic issues surrounding this product were quite dynamic considering the product's maturity. Two main business issues were present: an increasing production rate to meet increased demand, and increasing competition in the market. At the time of this study, the production rate of the 767 was three per month, but in the near term horizon a production rate increase of approximately 100 percent was anticipated. In fact the production rate has increased on this order since the study. All told, the production rate of all Boeing horizontal stabilizers at Vought was approximately 10 per month at the time of the study and has increased proportionally for all models since then. To reach these higher rates and fend off competition in the market place, Boeing established goals of 50 percent cycle time reductions in production, and 25 percent cost reductions for itself and its suppliers like Vought.

Vought responded to these goals with several strategies, including 1) increasing outsourcing content within its sub-assemblies, and 2) increasing flexibility in its assembly process. As discussed in this thesis, strategic objectives such as these are inseparable from the architecture and the assembly process. The following summarizes the impact of these two objectives on the example.

5.4.1.2.1 Increased Outsourcing

Like all major entities in the aircraft industry and companies in many other industries, Vought was reconsidering all in-house fabrication capabilities at the time of our study in order to focus on

a few core processes while outsourcing what was deemed not to be core to their business. Two events drove this. First, Vought had recently been purchased by Northrop-Grumman, so company-wide duplication was being eliminated while centers of excellence in particular fabrication and assembly techniques were being established. Vought was focusing much effort in composites manufacture though it had capabilities in machining, sheet metal forming, metal bonding, and numerous secondary processes. Second, in an effort to maximize efficiency, all processes that were not core were to be considered for outsourcing. Where Vought did not consider itself to be highly competitive in terms of cost and quality, outside suppliers (inside or outside of Northrop-Grumman) were to be sought. This included fabrication and assembly.

The possibility of increased outsourcing required us to understand the architecture of the horizontal stabilizer in order to reveal the integral characteristics of the assembly. This assessment would help determine which elements were appropriate for outsourcing, or whether changes could be made to make it more suitable for outsourcing. Currently, Vought remains the sole supplier to Boeing of the 747, 757, and 767 Horizontal Stabilizers and has a long-term agreement to retain this business given it meets the time and cost reduction goals. Vought assembles the three modules of the 767 horizontal stabilizer and ships them separately to Boeing, where final assembly occurs. At the time of this study, only the FTE sub-assembly was outsourced by Vought, and all upper skin parts were fabricated by Vought.

5.4.1.2.2 Increased Assembly Process Flexibility

The move for increased flexibility was driven by several anticipated benefits related to reduced cost and cycle time. These include the ability to adapt to changing productions rates in each model independently, and the adaptability of the process to new products of the same type. The changes in rate were expected to vary independently by model, e.g. the 767 rate could double while the rate in another product could decrease for a time, and then the opposite could occur. With the current single-use fixture-based process described below, these rate variations would have challenged Vought because dedicated work cells would lie empty while workers would be required to adapt to different products and their dedicated processes with which the roving workers' familiarity would be limited. Vought was actively increasing its business in wing-like structure at the time, so the ideal scenario would have Vought able to bring in new business to the flexible process to limit non-recurring cost and making their bids for that work very competitive. Increased flexibility lead us to two major options discussed below: either the parts must dimensionally align themselves, or the fixture must adapt to a variety of part sizes; each time consistent delivery of the KCs is the key measure of success.

The current assembly method described below, representative of all skin assemblies at Vought, relies on expensive hard tooling to establish part locations and support these large parts, operator intervention to overcome part and process variation, and custom shimming to fill inconsistent assembly gaps. Although the process delivers an acceptable product for the downstream assembly process, it is completely inflexible and has high labor content.

To make the assembly process more flexible and independent of hard locating fixtures, a flexible assembly concept was explored. This concept is based on using accurate assembly features on

parts to locate other parts that they mate with in the assembly. Without any analysis, we could define a set of tightly toleranced features on every part to be used during assembly so all mates would be accomplished. For example the upper skin assembly could be constructed by drilling accurate holes on the skins and stringers, and simply pinning these features together during assembly. However, because these parts are very long and are subjected to variations caused by thermal expansion and the shot peening process, a closer look shows that this approach would require high capability machines to create all these features, increasing the manufacturing costs. Also, as described below, not all mates between parts are equally significant.

A fixture-less process applicable to all skin assemblies showed the potential to reduce cost and assembly time, making Vought flexible to product variants and able to better utilize resources. The fixture-less process had to continue to produce acceptable assemblies in terms of quality. Also, increases in fabrication costs due to the new reliance on assembly features created during part fabrication could be minimized if the most important part features were identified. This problem is not straightforward. The remaining sections describe a systematic assessment of the architecture, and then a quantitative analysis of integral characteristics in the selected decomposition, with the goal being an assessment of the viability of a fixture-less process for this product.

5.4.2 Decomposition Analysis

This section describes the decomposition analysis of the right stabilizer. First, the KCs, derived from airplane KPPs associated with this module, are introduced. Second, a summary of the current assembly is described to show how the KCs relate to the assembly process. We next show with chains how the KCs are delivered, followed by an assessment of the integrality and integration risk of the current decomposition. Next, three alternate decompositions are described that reduce the integrality.

5.4.2.1 Key Performance Parameters and Key Characteristics

The KPPs for the horizontal stabilizer are aircraft loads carried by the structure as certified by the Federal Aviation Agency (FAA), aerodynamic specifications, and aircraft control and drag requirements from the FAA regulations. These KPPs lead to following KCs:

1. The loads requirement requires tightly controlled alignment of the inboard structure - the plus chords and end fittings; this is the "root alignment KC" (see Figure 5-29b)
2. The aerodynamic specifications require smoothly contoured surfaces in the airstream; this is the "aero smoothness KC" (see Figure 5-30)
3. The control requirement requires that the horizontal pivot freely with minimal wear of the blade seals against the side of the fuselage, so blade seals must be located accurately - this is the "blade seal KC" (see Figure 5-33)
4. The control requirement requires tightly controlled alignment of hinged parts - this is the "pivot alignment KC" (see Figure 5-28)
5. The drag requirement requires minimal asymmetry of this large structure - this is the "symmetry KC" (see Figure 5-28)

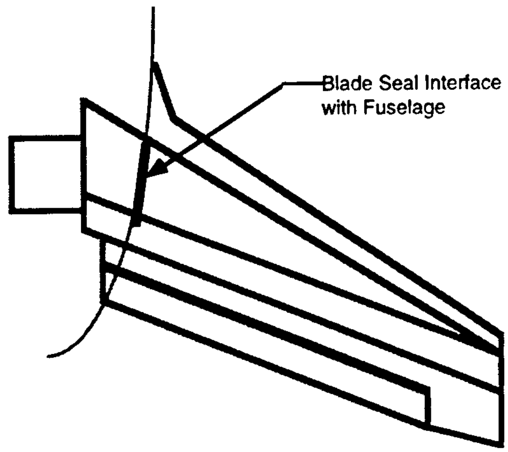


Figure 5-33. Blade seal interface with fuselage.

Wing roots require very tight tolerance alignment of the plus chord to other parts of the root in order to properly absorb the dynamic distributed loads [Niu]. This requirement is so important that, on some wing-like structures, if there is any out of tolerance alignment mismatch, a structural analysis simulation is required to ensure that proper safety margins are maintained for that set of parts; this is costly but is required if fit-up is not achieved.

Skin gaps are critical to the smoothness of the wing because the sealant used to fill these gaps (creating a continuous surface for airflow) will "flake out" if the gaps are outside the specified tolerance, either too small or too large.

The blade seals protect from the outside environment the open section in the aft fuselage in which the stabilizer pivots. They must fit tightly against the fuselage without causing extensive wear.

The large structure must pivot freely on the hinge points to reduce wear and avoid binding of the bearings under heavy load conditions. It is important to note that the actuation point is not subject to similarly tight control because the jack screw has a universal pivot that is robust to variation in the pivot attach point on the structure.

Finally, asymmetry of the structure forces the pilots to "trim" the aircraft, which increases drag and reduces the aircraft's range. This is not only a drag requirement but a significant focus of customers of these aircraft, who would like to eliminate the trimming of each aircraft individually.

These KCs are a representative set for the assembly. Others associated with contour of the aerodynamic surface, for example, could also be included but these five were selected for the analysis based on interaction with the host company and assessment of which drive the assembly trade-offs for the family of skin panels.[11]

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[11] Contour does not alter trade-offs because providing contour accurately is a requirement of any skin panel assembly process. If we were considering changing the assembly of the horizontal as a whole, where other contributors to contour (such as spacing of the spars) were to be included, a larger set of KCs would have likely been recommended.

5.4.2.2 Detailed Description of Existing Assembly Process

The following summarizes the right stabilizer and final assembly processes.

5.4.2.2.1 Assembly of the Right Stabilizer

Assembly of the full stabilizer structure occurs with the forward edge up, so the assemblies all rest on their aft features. The assembly is accomplished by loading the FTE and FTB in a large fixture to form the stabilizer shape, then each rib is put in place between the FTB and FTE, drilled, and riveted. Finally, the skin assemblies are put in place and the entire structure is riveted. Appendix E describes these steps in more detail.

Problems and other important observations include:

- A high risk situation is the inherent conflict between the two alignments in Figure 5-34, that either the plus-chord does not match the end fittings or the gaps between the skins and FTE, FTB are incorrect; this could lead to shimming, rework of the skin edges, or at worst scrapping the skin sub-assembly.
- The skin assembly currently meets the requirements consistently and mates smoothly with the other sub-assemblies most of the time.

5.4.2.2.2 Assembly of the Horizontal Stabilizer

Assembly of the left and right stabilizers to the center box at Boeing is accomplished by placing the wings and the center box on separate sets of locators of a large assembly tool with limited axis motion capabilities. Next the stabilizers are moved inboard, as shown in Figure 5-35, to allow

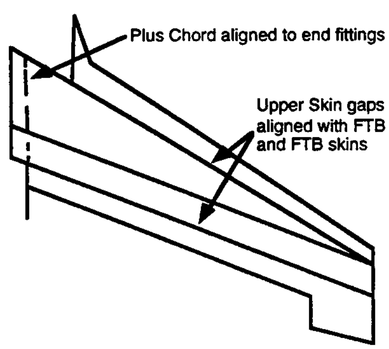


Figure 5-34. Assembled right stabilizer. The plus chord is located to the end fittings while the skins are aligned to the FTB and FTE skins (upper skin shown here from the top view, hidden line represents the plus chord).

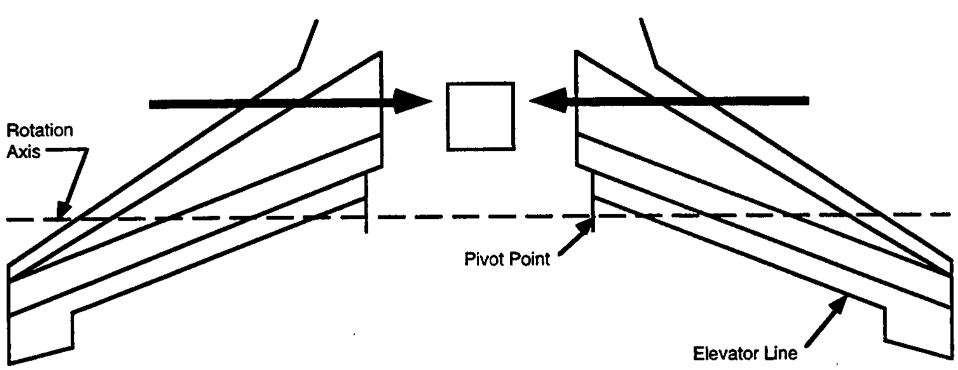


Figure 5-35. Assembly of the horizontal stabilizer.

plus chord and other parts to mesh with the center box skin. The assembly is shimmed and fastened.

5.4.2.2.3 Assembly of the Horizontal Stabilizer to the Fuselage

The assembled horizontal stabilizer is then joined to the 767 aft fuselage section at the pivot and actuation points. The large opening in which the Horizontal Stabilizer is free to move is tightly sealed by installing the blade seals into a set of holes previously drilled into the skins by Vought during the upper skin sub-assembly process.

5.4.2.3 KC Delivery in the Current Decomposition

The following describes the PKCs and AKCs derived from each KC based on assumptions about the existing process. Selected chains are shown, then an Interaction Matrix (IM) is described.

5.4.2.3.1 Assumptions

Based on observations of the final assembly process at Boeing, the locators for the modules were selected to explicitly control KCs 4 and 5, the pivot alignment and symmetry KCs. From here on these KCs are dropped from the analysis since they are completely controlled in the final assembly fixture. We can apply this reference frame information to capture some detail in the chains for each PKC.

5.4.2.3.2 PKCs and chains

5.4.2.3.2.1 Root Alignment KC

Four PKCs for this KC result from the decomposition. The inboard load alignment members are cut in four places: between each plus chord and the two end fittings, shown in Figure 5-36a. All four alignments are required for the KC to be delivered. Our focus here is on the upper skin only, and the lower skin portion of this KC will be similar to the analysis presented here. Of these two remaining gaps, we know from the above assumptions that the aft gap is delivered directly as the plus chord is located to the aft end fitting. Therefore, one PKC results from the root alignment KC:

PKC #1: alignment of the upper plus chord forward edge to the forward end fitting (Figure 5-36b).

Figure 5-36c shows a chain representation of how PKC #1 is delivered in the current decomposition. This chain representation is depicted on a sketch of three sub-assemblies: the FTB, FTE, and upper skin. The PKC is delivered at the module level, when the FTB and upper skin are mated. The root link lies in the FTE because, in the current assembly process, both the upper skin and FTB are referenced to locations in the FTE. The upper skin is referenced directly to features on the FTE (which can be used to specifically define link 2). The FTB is referenced to the FTE in a fixture (link 4) where the FTB, FTE, and upper skin are assembled. In fact, the only reference frame information that is required is the assumption that the two sub-assemblies that contain the end features are referenced to locations in a third element. This illustrates case 'b' of step 2 in the chain procedure where the root link lies in a third element. None of the

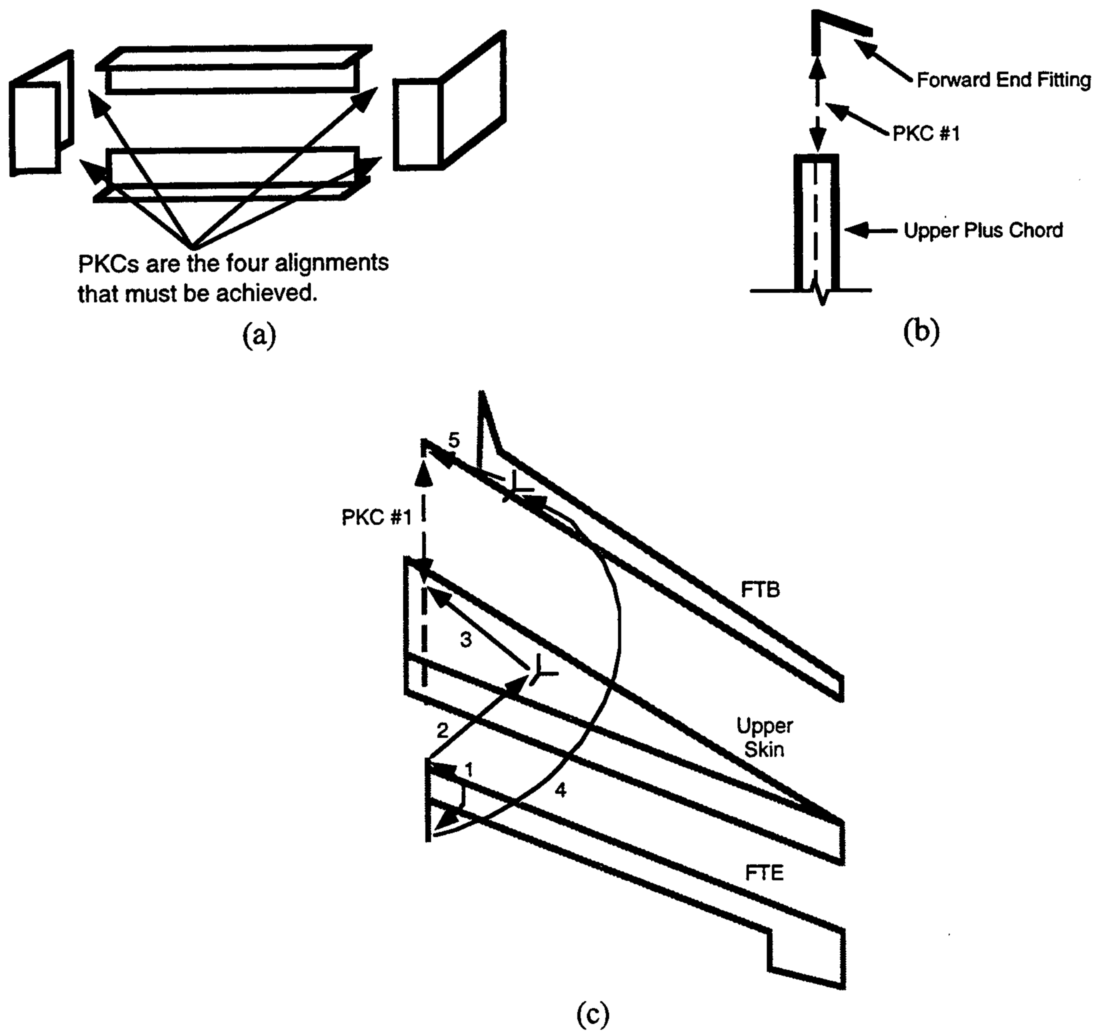
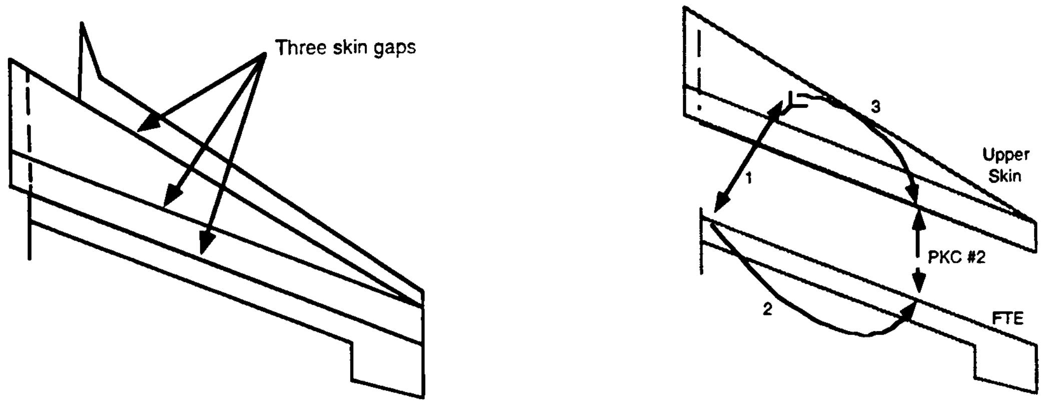


Figure 5-36. (a) Four alignments that must be achieved are PKCs for the root alignment KC (parts shown from Figure 5-29b). (b) For our analysis PKC #1 is the only KC required. (c) Chain to deliver PKC #1 in the current decomposition.

specific knowledge about the assembly process is needed to depict this chain. Links 2-5 in the two branches run from the FTE to the sub-assembly reference frame, and from the sub-assembly reference frame to the end feature. While the end features lie in *two* sub-assemblies, we find that the PKC is affected by dimensions within each of the *three* sub-assemblies and in two interfaces.

5.4.2.3.2.2 Aero Smoothness KC

There are three PKCs (see Figure 5-37a) for the aero smoothness KC: the gap between the forward skin and the FTB skin, the gap from the aft skin to the FTE skin, and the gap between the forward and aft skins. The former two are also present on the lower skin but are not included in this analysis. The forward and aft skin arrive constrained relative to one another, so the two gaps are related as described further below; for this reason I list these as "2a" and "2b." Therefore, two PKCs result for the aero smoothness KC:



(a) (b)

Figure 5-37. (a) Skin gaps that affect aerodynamic smoothness and (b) chain for PKC #2.

PKC #2a: gap between the aft skin and FTE skin
PKC #2b: gap between the forward skin and the FTB skin
PKC #3: gap between the forward and aft skins

Figure 5-37b shows a chain representation of how PKC #2 is delivered. In this case there is one interaction between sub-assemblies, the FTE and Upper Skin.

It is important to note that we see an indication of coupling between the two PKCs. That is, the two chains are shared by the same elements and share some common links between elements. If there are more PKCs than there are DOFs available to deliver the PKCs, the KCs are in conflict.

5.4.2.3.2.3 Other KCs

Three other KCs are included in the remaining analysis that described in Appendix E:

PKC #4: alignment of the blade seal holes relative to the stabilizer center line.
AKC #2: Plus chord position in y relative to the aft edge of the aft skin
AKC #3: Inboard sandwich of the splice plates, skins, and plus chord (spacing and contour).

5.4.2.3.3 Combined Representation of Chains

PKCs 1 and 2 are depicted on the WBS of the current decomposition in Figure 5-38. This view shows the coupling, where both PKCs are affected by the interface between the upper skin and FTE, and both chains are shared in the FTE and upper skin.

The four PKCs and AKCs 2 and 3 are shown in an IM representation in Figure 5-39. The matrix shows the aft fuselage and horizontal stabilizer hierarchically by the blocks along the diagonal. The horizontal stabilizer represented in the blocks B-E: the center box in B and right stabilizer sub-assemblies in C-E (only those that are pertinent to the KCs are shown). In this case all interactions between elements are shown above the diagonal (lower left of the matrix is not used). PKC #3 and AKC #3 are delivered with no interactions among these elements and are shown on the diagonal to denote that they are completely delivered in the Upper Skin sub-assembly. Note the large grouping of interactions between the Upper Skin and FTE. These are discussed in terms of the resulting coupling in the next section.

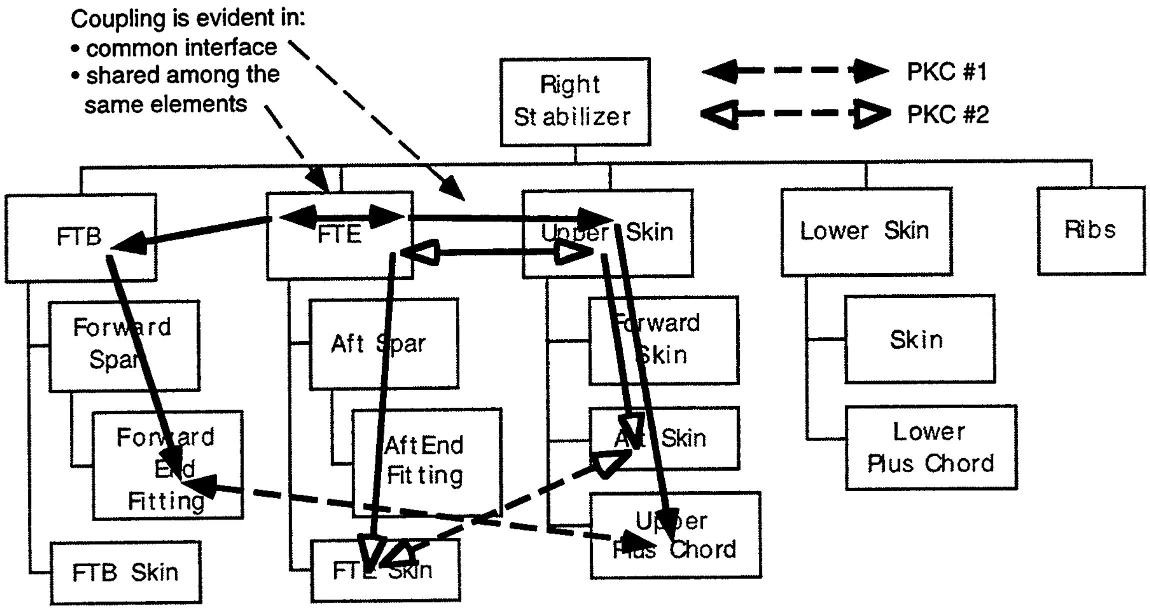


Figure 5-38. Chains depicted on the hierarchy of the current decomposition.

		A	B	C	D	E
Aft Fuselage	A			P4		
Center Box	B			A2		A2
Upper Skin	C			P3,A3	P1	P1,P2, P4,A2
FTB	D					P1
FTE	E					

Figure 5-39. Interaction matrix representation of the chains of delivery of the four PKCs and AKCs 2 and 3.

5.4.2.4 Architecture of the Current Decomposition

The chain structure metrics can be applied to this decomposition to reveal the integral characteristics.

5.4.2.4.1 Mapping Metric

Of the four PKCs only PKC #4 entails interaction of the stabilizer with the aft fuselage, so it has the greatest span. All the others are delivered in or below the level of the right stabilizer module. Four KC categories can be applied in the horizontal stabilizer[12], so long as we keep in mind that PKC #4 spans systems:

1. KC delivered in two modules (center box and right stabilizer) and multiple sub-assemblies of the right stabilizer (spans modules, height of the right stabilizer module).
2. KC delivered in two modules (center box and right stabilizer) and one sub-assembly of the right stabilizer (spans modules, height lower than the module).

[12] This list is similar to that in Section 4.4.1.4, but I categorize at the system and module levels instead of the product and system levels.

3. KC delivered in one module (right stabilizer) and multiple sub-assemblies of the right stabilizer (spans sub-assemblies, assume height of sub-assemblies[13]).
4. KC delivered in one module (right stabilizer) and one sub-assembly of the right stabilizer (spans components/parts)

The four PKCs and AKCs 2 and 3 are categorized as the following:

- Type 1: AKC #2
- Type 2: none
- Type 3: PKC #1, 2, and 4 (which has greater span overall)
- Type 4: PKC #3 and AKC #3

This set of categories will be used to rate the integrality of the decomposition and compare this baseline decomposition with the alternates described in Section 5.4.2.5. Using the MM scoring shown in Figure 4-21, we rate the integrality of these KCs as the following:

- PKC #1: yellow
- PKC #2: yellow
- PKC #3: green
- PKC #4: yellow
- AKC #2: red
- AKC #3: green

5.4.2.4.2 Coupling Metric

The IM in Figure 5-39 shows four KCs are potentially coupled: P1, P2, P4, and A2. These are all delivered in interactions of the upper skin and FTE. When we break these down into their degrees of freedom, we find there are three sets of coupled PKCs. PKCs 1 and 4 are coupled in the inboard-outboard direction, with PKC #1 being set directly and PKC #4 referenced from that point. PKC #2 and AKC #2 are coupled in the fore-aft direction, with PKC #2 being set directly and AKC #2 referenced from that point. And PKCs 1 and 2 are coupled in Øz. Øz could be set via an interaction with the forward end fitting in the FTB, which is referenced relative to the FTE pivot point, or set via the aft skin to FTE skin edge which is also referenced relative to the pivot point. This also alters the position of blade seal holes, which are constrained to a much looser tolerance than plus chord alignment so this is not seen as being coupled significantly.

The following integrality rating is derived from the CM scoring:

- PKC #1: yellow
- PKC #2: red
- PKC #3: green
- PKC #4: yellow
- AKC #2: red
- AKC #3: green

[13] This is not a given, but in all cases below the height is the maximum possible - sub-assembly.

The coupling of PKCs 1 and 2 is the most complex interaction we observed in this case study because no one reference point was consistently used in the process, while the other two couplings were referenced in the same manner each time. This coupled pair is the focus of the remaining decomposition tradeoffs described below.

5.4.2.4.3 Critical Path Metric

Figure 5-40 shows the IM of Figure 5-39, with a critical path containing the right stabilizer, horizontal stabilizer, and mating of the horizontal stabilizer to the fuselage superimposed.[14] All shaded regions represent work on the critical path, and the content of those cells shows where KCs interact with the critical path. Note that the sub-assembly on the critical path was not identified.

All but PKC #3 and AKC #3 lie on the critical path of assembly and are scored yellow in this metric.

5.4.2.4.4 Summary of Architectural Complexity

The integral characteristics in this case are clear. PKC #3 and AKC #3 are modular in every measure: they map to a single sub-assembly, are decoupled, and are off the critical path. PKC #1, 2, and 4, and AKC #2 have an integral mapping, are coupled to another of these integral characteristics, and all lie on the critical path. Therefore, all four are identified as integral characteristics.

5.4.2.4.5 Integration Risk

The integration risk metrics are now applied to each integral characteristic. All four integral characteristics exhibit high integration risk because they are delivered in multiple sub-assemblies made by different suppliers, including the upper skin that was planned to be converted to new fabrication and assembly technologies. Again, the most prominent attention is paid to the coupling of PKCs 1 and 2, which are both integral and high risk, and were already delivered in an inconsistent process that was not fully capable.

		A	B	C	D	E
Aft Fuselage	A			P4		
Center Box	B			A2		A2
Upper Skin	C			P3,A3	P1	P1,P2, P4,A2
FTB	D					P1
FTE	E					

Figure 5-40. Critical path superimposed on the IM of Figure 5-39.

[14] See Section 4.4.2.3.3 for a discussion of how the critical path is depicted on an IM.

5.4.2.5 *Alternate Decompositions*

Three alternate decompositions have contrasting architectures and levels of integration risk when compared with the current decomposition. At the time of this investigation we only considered the "pivot rib assembly" decomposition (alternate #2) discussed below. I present two alternatives here and then a hybrid of the two. I created alternate #1 in hindsight. In fact none of the three could have been considered at the time of the study because the design was fixed and Vought was limited to process changes, not product changes like new decompositions, in their cost and cycle time reduction efforts. The reasons that design changes would have been required are discussed in each case below.

5.4.2.5.1 Alternate #1: Main Torque Box Sub-assembly

The main torque box sub-assembly alternate decomposition includes three sub-assemblies, an FTB, FTE, and Main Torque Box (MTB) that contains the spars and end fittings allocated to the FTB and FTE in the current decomposition. The MTB has five components as shown in Figure 5-41: the forward spar, aft spar, upper skin, lower skin, and the ribs.

5.4.2.5.1.1 Chains

PKC #1 is now delivered in the MTB sub-assembly, as depicted in Figure 5-41 where all links are found just in the sub-assembly as opposed to in multiple sub-assemblies. PKC #2 is still delivered at the module level because the chain crosses sub-assemblies. There is the opportunity to decouple the two PKCs because there are no shared interfaces among elements. The branch of AKC #2 in the right stabilizer module is now delivered MTB sub-assembly, so the height is reduced. The remaining three KCs are unchanged. Figure 5-42 shows the IM for this decomposition,

5.4.2.5.1.2 Resulting Architecture

Alternate #1 is more modular than the current decomposition. Noting that PKC #4 retains its span across systems, the same four categories of mapping can be used. In this decomposition

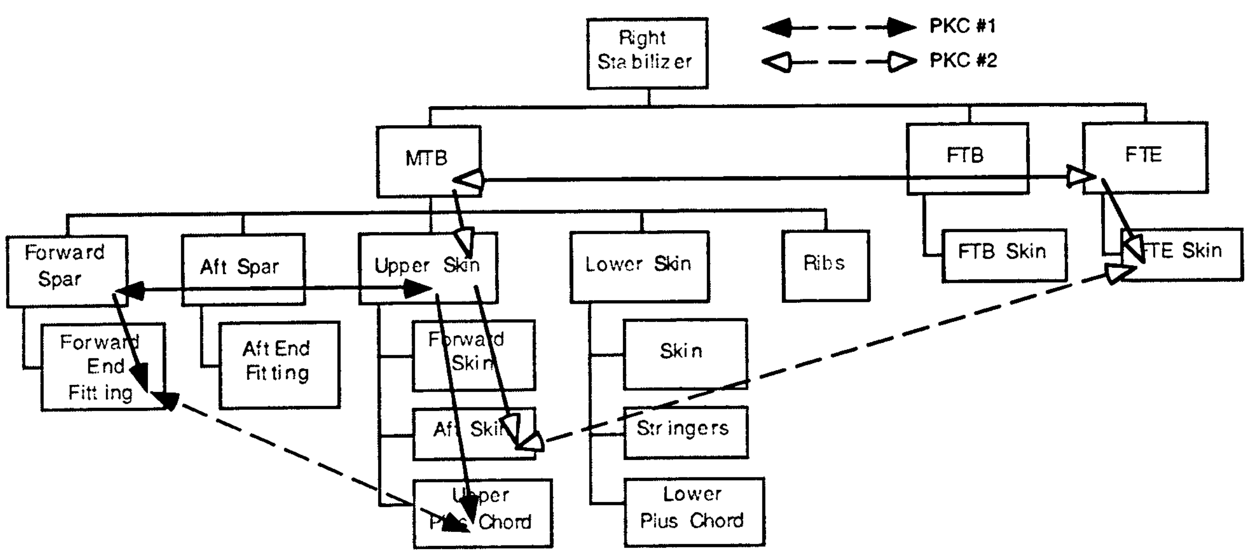


Figure 5-41. Hierarchy and chains of alternate decomposition #1.

		A	B	C	D	E	F	G
Aft Fuselage	A			P4				
Center Box	B			A2				
Upper Skin	C			P3,A3	P1	P1,A2		P2, P4
Forward Spar	D							
Aft Spar	E							
FTB	F							
FTE	G							

Figure 5-42. IM for the main torque box alternate decomposition. Note that components C, D, and E are three of the five that comprise the MTB sub-assembly of the right stabilizer.

PKC #1 and AKC #2, like PKC #3 and AKC #3, are delivered in a single (albeit more comprehensive) sub-assembly in the right stabilizer - components C, D, and E in the IM. PKC #1 is reduced from category 3 to 4, and AKC #2 is reduced from category 1 to 2. The mapping of PKCs 2 and 4 is unaffected.[15] The four PKCs and AKCs 2 and 3 are categorized as the following in this decomposition:

- Type 1: none
- Type 2: AKC #2
- Type 3: PKC #2 and 4 (which has greater span overall)
- Type 4: PKC #1 and 3 and AKC #3

The following are the MM scores

- PKC #1: green
- PKC #2: yellow
- PKC #3: green
- PKC #4: yellow
- AKC #2: yellow
- AKC #3: green

Two potential sets of coupled KCs are shown in the IM: PKCs 2 and 4, and PKC #1 and AKC #2. A DOF analysis shows that PKC #1 and AKC #2 are not coupled. Only PKCs 2 and 4 are coupled, so both are scored yellow on the CM. PKCs 1 and 2 are now decoupled since PKC #1 is fully delivered in the MTB and PKC #2 can be set directly without conflict KC. In addition, AKC #2 is decoupled from PKC #2. Finally, the blade seal holes can now be used as the MTB reference point in the inboard/outboard direction, so PKC #4 is decoupled from PKC #1.

Figure 5-43 shows the IM of Figure 5-42 with the new critical path superimposed. I assumed that the MTB sub-assembly is on the critical path due to its complexity relative to the FTB and

[15] As an additional note, the contour of the stabilizer is altered. The contour of the upper skin is now set in the sub-assembly as opposed to assembly of the right stabilizer.

		A	B	C	D	E	F	G
Aft Fuselage	A			P4				
Center Box	B			A2				
Upper Skin	C			P3,A3	P1	P1,A2		P2, P4
Forward Spar	D							
Aft Spar	E							
FTB	F							
FTE	G							

Figure 5-43. Critical path superimposed on the IM of Figure 5-42.

FTE. In this case the change in decomposition does not alter the relation of the KCs to the critical path.

5.4.2.5.1.2.1 Summary of Architectural Complexity

The integral characteristics in this case are reduced. PKC #3 and AKC #3 remain modular in every measure. PKCs 2 and 4 retain a relatively complex mapping (type 3, and PKC #4 spans systems) and lie on the critical path, but are no longer coupled to other KCs. PKC #1 and AKC #2 were both reduced in their mapping by one category, are now decoupled, but remain on the critical path. The relative integrality of the four integral characteristics has been reduced.

5.4.2.5.1.3 Integration Risk

Organization boundaries for potentially outsourced sub-assemblies have been reduced. In this decomposition the FTB has a role only in PKC #2 . The FTE, which was already a purchased assembly, no longer has a role in any coupled KCs. In addition, depending on the decomposition selected within the MTB, some components may be better candidates for outsourcing than were previously when they were part of the delivery of characteristics that rated more integral in the three metrics.

5.4.2.5.1.4 Issues

Several issues must be considered with this decomposition:

- if the Upper skin was already on the critical path, the new decomposition may grow the cycle time for the entire assembly as additional work has been added from the FTE and FTB sub-assemblies to left/right stabilizer assembly, and work has been transferred from left/right stabilizer assembly to the MTB sub-assembly so it remains on the critical path
- the FTB and FTE may not be stable sub-assemblies without the spars, which complicates the decision of outsourcing due to the support that would be required in transit
- significantly different tooling would be required at left/right stabilizer assembly, and an additional complex tool for building the MTB, on the order of the scale of the module assembly fixture, would have to be added

- no design change is evident, but different joints would be made, between the spars and FTE and FTB, then are currently made at left/right stabilizer assembly that would require analysis for accessibility.

5.4.2.5.2 Alternate #2: Pivot Rib Sub-assembly

The "pivot rib sub-assembly" alternate decomposition includes a sixth sub-assembly in addition to the FTB, FTE, and upper skin, lower skin, and the ribs. The pivot rib sub-assembly contains the end fittings and two plus chords, the four parts of the inboard structure allocated to the other sub-assemblies in the other decompositions. The WBS is shown in Figure 5-44.

5.4.2.5.2.1 KCs and Chains

PKC #1 is delivered in a single sub-assembly, while PKC #2 is still delivered at the module level, as shown in Figure 5-44. There is no coupling of PKCs 1 and 2. AKC #2 is redefined in this decomposition because the dimension of interest, the position fore/aft of the plus chord relative to the aft end fitting, is also delivered in the pivot rib sub-assembly. The new AKC is:

AKC #2: Plus chord position in y relative to the end fitting feature that mates with the aft spar of the center box.

The other KCs are unchanged. Figure 5-45 shows the IM for this decomposition.

5.4.2.5.2.2 Resulting Architecture

Alternate #2 is more modular that either the current decomposition or alternate #1. In this decomposition, the mapping is further simplified. PKC #1 and AKC #2 are delivered in a single and more simple sub-assembly. PKC #1 is reduced from category 3 to 4, and AKC #2 is reduced from category 1 to 2. The mapping of PKCs 2 and 4 is unaffected. The four PKCs and AKCs 2 and 3 are categorized the same and their MM scores are the same as in alternate #1.

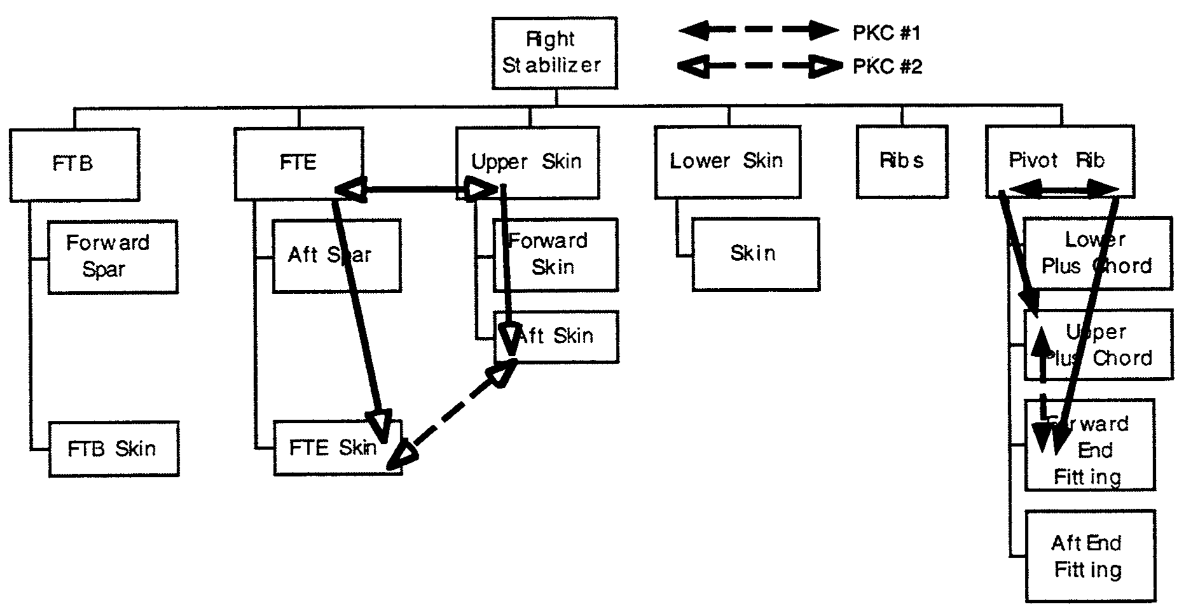


Figure 5-44. Hierarchy and chains of alternate decomposition #2.

		A	B	C	D	E	F
Aft Fuselage	A			P4			
Center Box	B				A2		
Upper Skin	C			P3,A3			P2, P4
Pivot Rib	D				P1,A2		
FTB	E						
FTE	F						

Figure 5-45. IM for the pivot rib sub-assembly alternate decomposition.

The only potential coupling involves now involves PKCs 2 and 4, and they are in fact coupled.

Figure 5-46 shows the IM of Figure 5-45 with the critical path superimposed. In this case the change in decomposition does alter the relation of the KCs to the critical path, as PKC #1 no longer resides on the critical path.

5.4.2.5.2.2.1 Summary of Architectural Complexity

The integral characteristics in this case are reduced like in the case of alternate #1. In this case PKC #1 was not only both reduced in its mapping by one category and decoupled, but now is also off the critical path.

5.4.2.5.2.3 Integration Risk

Similar supply chain opportunities exist with the increased modularity of this decomposition. In addition to those discussed above, the pivot rib assembly is itself a good candidate for outsourcing and/or implementing newer technologies like full integrated high speed machining of the parts in a unitized part. This reduces the weight and, depending on the competency of the source, could improve cost, quality, or both.

		A	B	C	D	E	F
Aft Fuselage	A			P4			
Center Box	B				A2		
Upper Skin	C			P3,A3			P2, P4
Pivot Rib	D				P1,A2		
FTB	E						
FTE	F						

Figure 5-46. Critical path superimposed on the IM of Figure 5-45.

5.4.2.5.2.4 Issues

Several issues must be considered with this decomposition:

- The most critical design issue associated with this decomposition is the difficulty of making the plus chord to upper skin joint after the stringers have been attached to the skin. The fasteners that attach the skins, plus chord, and other parts into a sandwich at the inboard end require access from the side where the stringers are located (the underside shown in Figure 5-32). In the existing upper skin it is already difficult to access that joint and requires substantial fixture support to sustain the forces that occur while drilling the holes. If this were to occur during assembly of the right stabilizer, the joint as designed would be inaccessible and the fixture as currently designed could not sustain the drilling forces. The joint would have to be redesigned.
- The mate of the end fittings to the spars could also be difficult and require shims. While these mates were not identified as KCs in our study of the assembly, these also lie on important load paths and may require substantial attention to correct any fit-up problems created by the alternate mating approach.
- Unlike alternate #1, the stability of all the assemblies is maintained. However, the inboard region of the skins would not retain their contour without the presence of the plus chord and splice plates, which could be an issue both in fastening of the stringers to the skins and in assembly of the skin at left/right stabilizer assembly.

5.4.2.5.3 Alternate #3: Hybrid of Alternatives 1 and 2

A hybrid of the two alternatives is the most modular of all the alternates. The decomposition is summarized in the IM of Figure 5-47. The hybrid further simplifies the MTB by accomplishing PKC #1 and AKC #2 in the single pivot rib component, removing PKC #1 from the critical path and reducing the MM score for AKC #2 to green. In fact no KCs are accomplished in the assembly of the MTB, which simplifies the process and fixture construction. Though it is the most modular option, alternate #3 carries with it the advantages and disadvantages of the other two alternates. The disadvantage of the difficult joint in alternate #2 would need to be addressed, as would the unstable sub-assembly problem of alternate #1.

		A	B	C	D	E	F	G	H
Aft Fuselage	A			P4					
Center Box	B				A2				
Upper Skin	C			P3,A3					P2, P4
Pivot Rib	D				P1,A2				
Forward Spar	E								
Aft Spar	F								
FTB	G								
FTE	H								

Figure 5-47. IM of a hybrid of the two alternate decompositions.

5.4.2.6 Architecture Conclusions

Figure 5-48 serves as a decision tree summarizing the decomposition alternatives that I argue can and must be discovered and analyzed as part of concept design. Recognizing that each comes with issues and alters the architecture of the product, the IPT can perform a structured assessment of the decomposition alternatives in candidate concepts in time to alter the outcome and avoid being constrained downstream when there is little flexibility to re-address past decisions.

As described above, the architecture of each is unique and poses different levels of integration risk. All three alternate decompositions are more modular than the current decomposition. Alternate #2 is more modular than alternate #1 by reducing the KC interactions on the critical path. The hybrid is the most modular because it further reduces interactions with the critical path and the MM score of an additional KC. All three alternates pose low integration risk if assembly features, suppliers, and technologies are carefully selected on the two remaining integral characteristics.

5.4.3 Quantitative Analysis of a Fixtureless Assembly Process for the Upper Skin in the Current Decomposition

Though it posed the greatest integrality and integration risk, the current decomposition could not be altered with the process for the upper skin. In order to investigate the ability of a new feature-based process to deliver the KCs, I performed a quantitative variation analysis of the upper skin assembly using VSA. The assembly features that I selected are shown in Figure 5-49 and described in detail in Appendix E and Cunningham et al [1996].[16]

The focus of the analysis was on PKCs 1 and 2. These were translated into an AKC (see Figure 5-50:

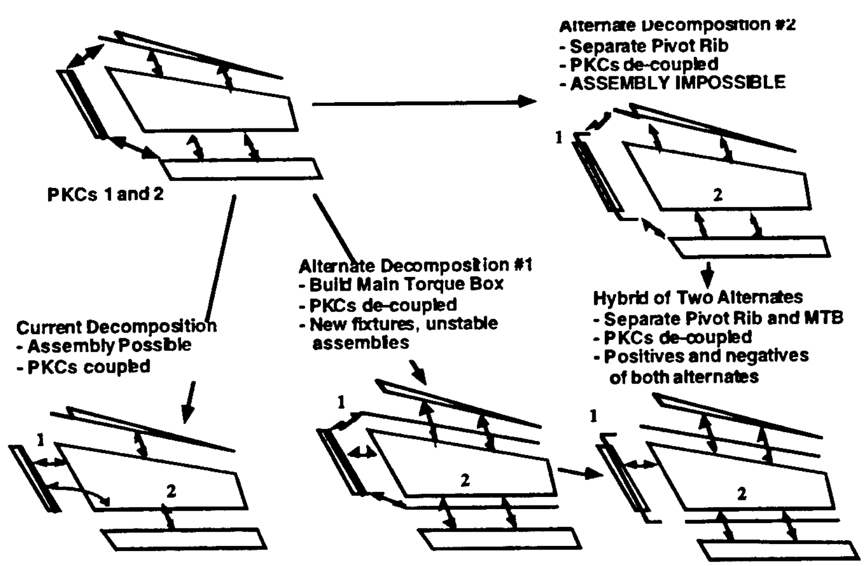


Figure 5-48. Four decompositions of the horizontal stabilizer assembly.

[16] Adams [1998] studied this set of features in developing his assembly feature design tool. They were verified to be a set suitable to the intended datum flow and assembly sequence [Cunningham et al, Mantripragada et al].

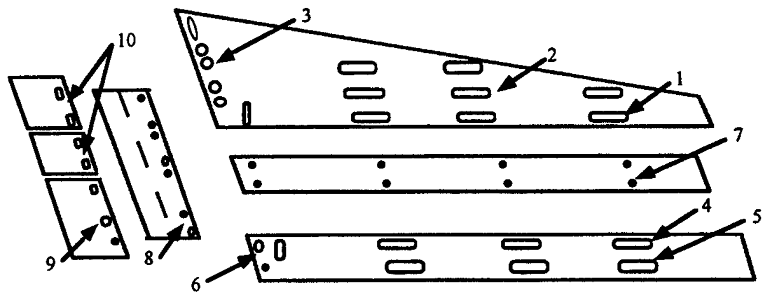


Figure 5-49. Proposed mating features for a feature-based upper skin assembly process, described in Appendix E.

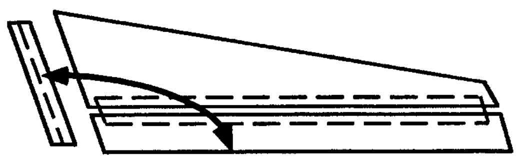


Figure 5-50. AKC #1.

AKC #1: Plus chord angle relative to aft skin aft edge.

The ability to deliver this AKC became one criterion for our process, in addition to economic and capacity requirements described by Cunningham et al [1996] and Anderson [1997]. My intended datum flow with the set of mating features was to attach the two skins through stringer #3, and then attach the plus chord to the hole and slot at the extreme fore/aft locations of the aft and forward skins, respectively, to create the proper angle. This is illustrated with a "KC Deliverability Map" shown in Figure 5-51.

The analysis began with construction of a nominal skeleton of the parts with representative dimensions. The nominal skeleton included the assembly features. The skeletal model was related to an assembly sequence consistent with the intended datum flow. A notional check fixture was created to check the angle.

The most important step involved determining the proper capability data to model. I gathered data based on actual machine and fastening capabilities for both existing machines and potential future equipment. The data was gathered to match the links in the chains that involved how the mating features were created at the fabrication level, and how assembly of the parts would be accomplished. Included were part variations that result from processing steps like shot peen. In all, nineteen variations were associated with the skeletal model.

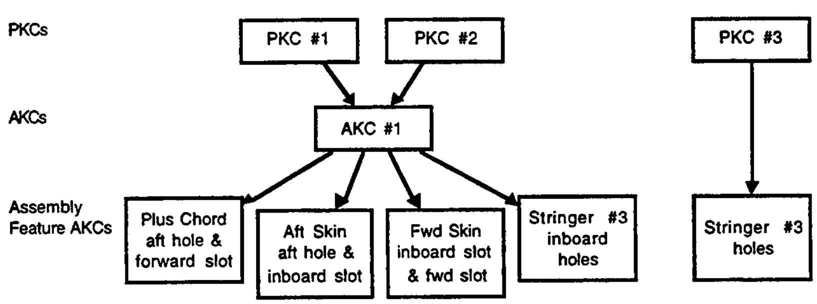


Figure 5-51. PKC and AKC relationships for the feature-based process.

The key dimension, as indicated by Pareto analysis in VSA, was the accuracy of the hole locations on the inboard end of stringer #3. These holes create the inboard alignment of the hole and slot on the aft and forward skins, which in turn locate the plus chord relative to the aft skin aft edge. The second most important dimension was the perimeter accuracy of the aft skin. The plus chord itself, which is subject to large dimensional uncertainty, was not a major contributor based on the way that I constrained it at the extreme forward and aft ends.

The output of VSA is a process capability chart at the assembly level based on Monte Carlo simulation of the user input process capabilities and assembly sequence. Figure 5-52 shows an example of such a chart. The distribution shows the number of assemblies that are "high", i.e. above the upper specification of the assembly tolerance, and the number "low", i.e. the number below the lower specification.

The holes on stringer #3 were to be created by a mill whose capability was being debated. I investigated several cases with VSA. The graph in Figure 5-53 shows five cases that were considered. The first four are listed as .002, .004, .006, and .008, which refers to the capability of the mill to be used to create the stringer inboard holes. The number refers to the hole centerline location capability of the machine in thousandths of an inch, to $C_{pk}=1$. Each case shows the percent of assemblies predicted to be low and high, i.e. outside the specifications. The .002 mill would have been the most costly, and 8 percent of the assemblies would still have been

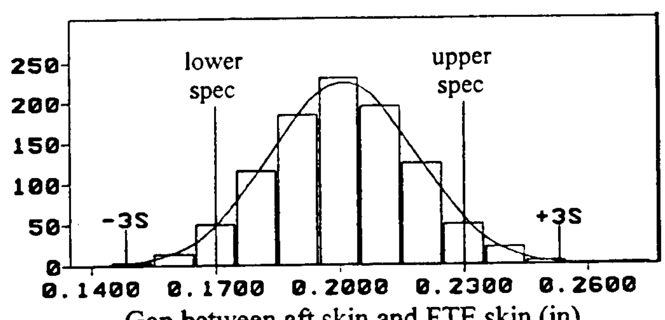


Figure 5-52. Sample output from VSA: process capability chart.

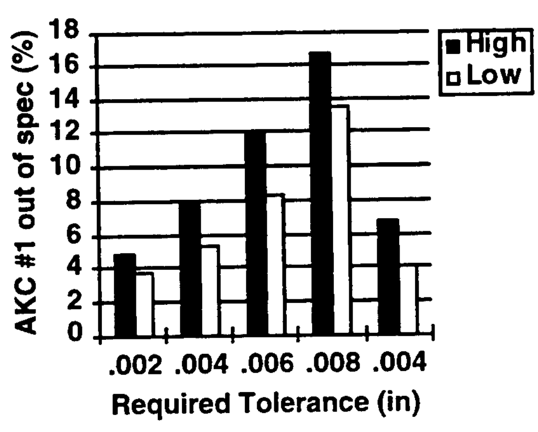


Figure 5-53. Predicted number of assemblies out of spec for five cases of stringer mill capability.

out of spec. The .004 mill is an existing capability, and the other two are low cost alternatives that would have been attractive due to the expanded capacity. The fifth entry in Figure 5-53 refers to the use of the .004 mill for the stringer holes, and a low cost improvement to the machine that creates the aft skin perimeter. Notice that this option has better results than the first .004 entry, with 10.7 percent of entries out of spec.

The results of VSA quantitatively back what we have showed qualitatively: PKCs 1 and 2 are integral and high integration risk KCs. With the VSA results, we now see that an unacceptably high number of assemblies would not be in spec based on AKC #1. This means that the pursuit of a feature-based process with this architecture introduces extremely high risk. Two alternatives are possible:

1. Reconsider the decomposition and attempt to decouple the PKCs, which throughout the course of our study was not an option.
2. Investigate other candidate processes, one of which that we investigated proved to be too costly [Anderson].

5.4.4 Summary of the Horizontal Stabilizer Example

The horizontal stabilizer example illustrates a much more complex architecture tradeoff than the other examples in this chapter, and shows how the chain approach can guide an architecture study toward a quantitative variation analysis.

5.5 Other Examples and Case Studies

Every product is developed to meet some company strategy, so the examples in this chapter give just a small glimpse into this broad topic. Other products that have been studied in the literature exemplify trade-offs involving manufacturing, assembly, platform, and technology strategy, where dimensional characteristics could be studied with the same chain procedure and metrics to assess the appropriateness of the resulting architecture. These include:

- a study of several product design issues driven by assembly at Nippondenso, including a large family of panel meters for automobiles [Whitney 1993, Whitney 1988]
- common components in power tools at Black and Decker, and other examples [Meyer and Lehnard]
- platform strategies in small electronic products like the Sony Walkman, and other products [Sanderson and Uzmari]
- market strategies in copiers at Xerox [Clausing, Sontow]
- the architecture of a rapid prototyping machine [Ulrich and Eppinger]

5.6 Chapter Summary: Leading to the Chain Metrics Method and JSF Case Study

This chapter makes two main points. First, architecture tradeoffs involving a broad range of technical, producibility, and strategic drivers can be found in many products, and are common in that they present a complex problem that must be analyzed during concept design. Second, chains and the metrics developed in Chapter 4 are applicable to this broad range of problems.

The horizontal stabilizer example especially emphasizes a key argument of this research: architecture must be considered in concept design when decomposition is selected because there is no opportunity to do it downstream in the process. In our study of this existing product, we were constrained to the existing decomposition despite the fact that the integral and coupled nature of the chains inhibited a strategic objective that involved developing a flexible assembly process. Though we were not present at the time of concept design of this product, the description in Section 5.4 is indicative of what can happen in a development program where a "rush to judgment" about decomposition occurs without this systematic approach to studying the architecture. Consider the scenario where this was a real development program, the current decomposition had been selected early before the design was well-defined, and part and process definition proceeded until eventually a variation analysis to study KC delivery was performed like that described in Section 5.4.3. From this variation analysis a structured system level study should identify the coupling issues we indicate here, and should guide the IPT to alternatives. However, in this scenario and in other real development programs, the decomposition decision represents a commitment from which a great deal of the design process is let loose to proceed. Changing a decomposition downstream would be a monumental undertaking, requiring vast redesign, changes, and lost time that would delay substantially the introduction of the new product into the market. The associated costs would be prohibitive. The opportunity to alter the architecture, and to recognize the associated integration risk, is at the time of the decomposition selection alone.

The order of the analysis as presented in Section 5.4 is critical: a qualitative, structured architecture and integration risk assessment before the concept and decomposition is selected, and then the detail design that leads to a highly quantitative analysis. The next two chapters of the thesis develop a method to achieve just that. It combines the architecture and decomposition 3D IPD framework, chain capture procedure, and metrics into a method for a cross-functional IPT to investigate candidate concepts and decompositions in the context of their architecture and integration risk. Chapter 6 describes the method. Chapter 7 illustrates the method in the context of the JSF case study.

6. The Chain Metrics Method

This chapter explores the second theme of the thesis: the method and 3D IPD environment in which the chain procedure and metrics should be applied during concept design. While Chapter 4 developed the specific chain procedure, presentation guidelines, metrics, and quantitative analysis techniques, the Chain Metrics Method (CMM) developed in this chapter presents the bigger picture for utilizing these techniques. The CMM defines the roles IPT members play in a framework for identifying the integral characteristics and integration risk during concept design, coordinating design, process, and strategic decisions that affect the integral characteristics, and documenting the architecture for subsequent phases. The CMM addresses the drivers of decomposition of complex products with integral characteristics as discussed in Chapter 3, specifically presenting an open trade space for modular and integral preferences and functional and physical domain decomposition decisions. The CMM is designed to give structure - an agenda - to IPT interactions that affect the architecture. These interactions occur between different disciplines in the IPT, between sub-teams assigned to different elements of the decomposition, and between sub-teams assigned to different concepts or concept variants. The IPT assesses the architecture of each concept design by analyzing its candidate decompositions with chains and the metrics.

Figure 6-1 repeats the decomposition and architecture framework shown in Figure 4-1. This chapter develops this framework into the CMM. Section 6.1 describes four steps of the method and the roles that IPT members play in each step. Section 6.2 explains how the insight into the architecture gained by the CMM provides the team with the best opportunity to control the architecture and recognize and mitigate integration risk.

6.1 The Chain Metrics Method: Steps and IPT Roles

This section describes the four steps of the CMM: preparation, execution, iteration, and selection and documentation. Each step is accompanied by a discussion of the roles that IPT members from different disciplines play. Particular focus is on the types of decisions that influence physical domain decomposition and integration risk. The section builds the four steps into the full CMM presented in Section 6.1.5.

The CMM is built in three columns that match the three main disciplines - design/performance, producibility, and strategy - whose active role in shaping architecture was discussed and illustrated in Section 3.2 and the examples of Chapter 5. This basic structure is represented in the framework in Figure 6-1. The way to read each figure in this section is to scan down the

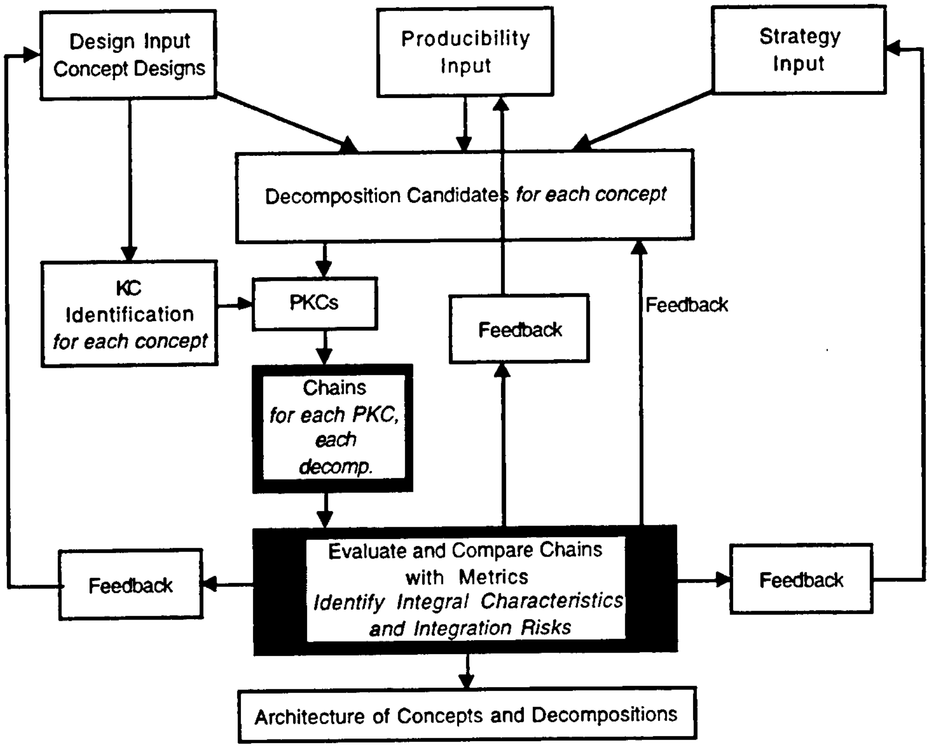


Figure 6-1. Decomposition and architecture framework that forms the basis for the CMM.

three columns that represent the tasks performed in different disciplines, and to look for the tasks that cross the discipline lines and the arrows that depict interaction between the disciplines.

6.1.1 Step 1: Preparation

Figure 6-2 shows the preparation step of the CMM. The method begins after an assessment of customer and corporate needs are formulated into a set of requirements for the development program. These are taken a general input to the top level decisions made by each main group shown at the top of the process, discussed immediately below. There are two outputs of this step: 1) a set of KCs that are to be converted to PKCs, the subjects of chain analysis, and 2) a set of candidate physical decompositions for each concept.

The design team generates and assesses all concepts for performance and cost - and, for products like aircraft, weight. For highly integral things like aircraft and cars, this assessment can be a lengthy process requiring many iterations and simulations and the use of highly integrated computer-based design tools. Inevitably, each concept will have excess performance along some measures while being marginal or even unsatisfactory on others. The designers will try to trade off the excesses in the hope of improving the marginal areas, but even the best concept will still be marginal along some measures. The marginal set comprises, by definition, the Key Performance Parameters (KPPs) for that concept.[1] These KPPs provide all the IPT members with a common framework for studying that concept. The IPT will focus on the KPPs to improve their margins and keep performance from falling below critical thresholds.

[1] Refer to the definitions that appear in Section 4.1.7.1.

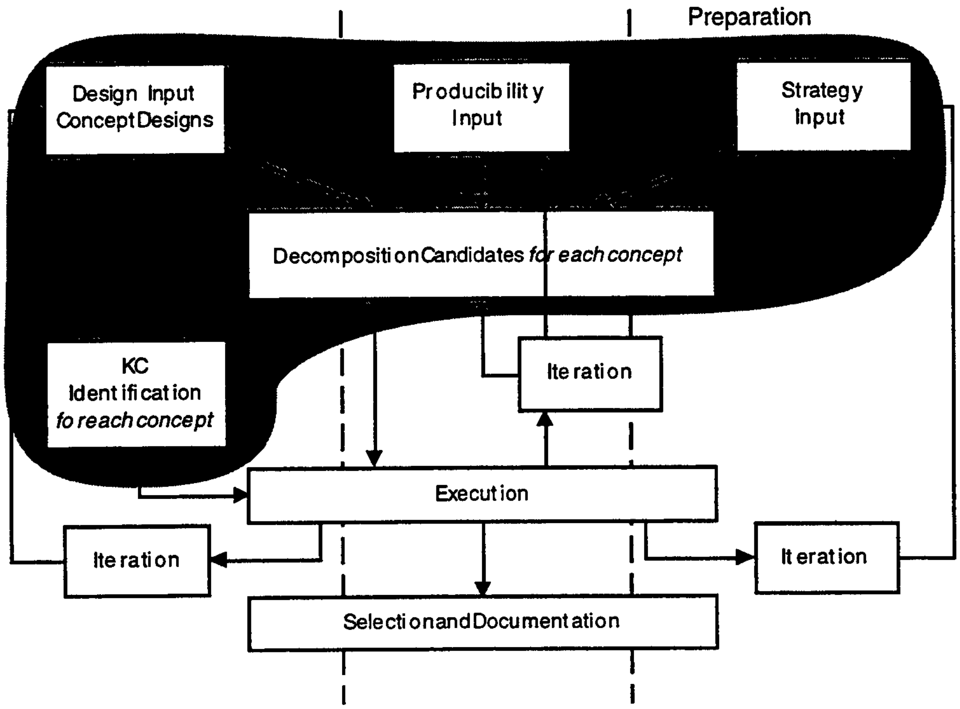


Figure 6-2. The preparation step of the CMM.

The designers then convert the KPPs into Key Characteristics (KCs), the physical attributes that deliver the KPPs. In general, the KCs will be different for each concept because the KPPs are. The KCs should be identified by a process like EQFD and by using computer-aided design tools. The KCs will be further decomposed into specific dimensions called Product (PKCs) in preparation for chain analysis.

Concept designs are developed in an IPD framework with explicit attention to producibility and strategic objectives. The first step for the producibility team represented in the CMM is to develop some overarching options for the assembly and manufacturing system. This is an increasingly common activity in IPTs in early design, and production system design tools are receiving attention formerly reserved for product design [e.g. Nevins and Whitney]. These system options may include:

- some of the manufacturing strategy options listed above for ease of assembly,
- certain tooling methods to align parts,
- specific breaks in the decomposition to allow for automation, or
- certain decompositions that will allow specific processing steps to occur at specific points in the process.

The CMM represents strategy as a third group, but in fact the strategic objectives for a product to fit into the broader corporate strategy can come from many different inputs. The strategic objectives that particularly weigh on physical decomposition, listed immediately below, should be formulated into a structured input for the method.

The decompositions are generated by the IPT based on the input from each of the three main groups. Each group makes decisions that influence decomposition. Throughout this thesis there

have been examples of these decisions, including:

- design/performance - largely functional decomposition, or the decisions to assign many functions to one or many of the same physical elements
- producibility - the choice of how the product should be physically decomposed into appropriate elements for the planned assembly and fabrication processes
- strategy - the choice of what physical elements will be common to a platform, how to support and re-use some physical elements, technologies to pursue, suppliers to team with, and physical elements to outsource.

The CMM does not generate candidate decompositions. Rather it reflects the fact that this diverse set of decisions is unlikely to lead to a satisfactory solution for all. Rather, each IPT sub-group will pose desires for the physical decomposition and candidates will be selected for further analysis with chains and the metrics.

6.1.2 Step 2: Execution

Figure 6-3 shows the execution step of the CMM. Three steps are involved: 1) conversion of KCs to PKCs, 2) chain capture, and 3) chain analysis with the metrics and, perhaps, quantitative analysis of the most integral and high risk characteristics. The output of this step is insight into the architecture of candidate concepts in the form of a set of integral characteristics and an assessment of the integration risk.

Based on the terminology and description in Chapter 4, design and producibility representatives share the roles of PKC identification and chain capture because the inputs of each group are

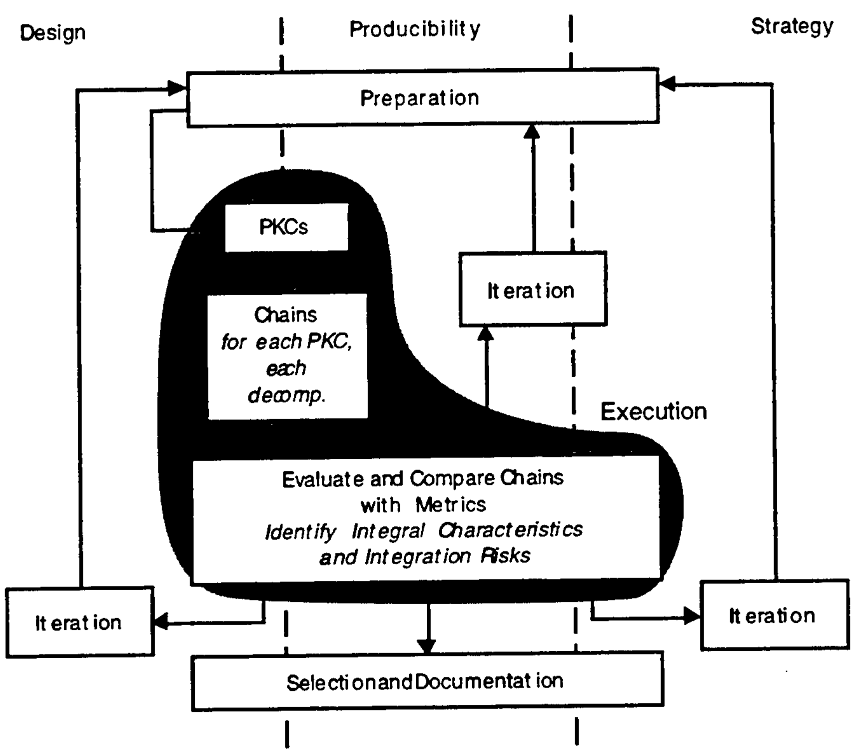


Figure 6-3. The execution step of the CMM.

required. The metrics depict the integration concerns of all members of the IPT, so the analysis block in Figure 6-3 is shown to cross all the disciplines. Chapter 7 presents how the execution step can be tailored to be performed in stages that match with the product hierarchy and team organization.

6.1.3 Step 3: Iteration

Figure 6-4 shows the iteration step of the CMM. The insight into architecture attained in the execution step affords the IPT the opportunity to consider alternative concepts and strategies prior to the selection of a concept and decomposition.

Four types of iteration are depicted in the CMM. The first involves the multi-disciplinary task of developing additional decomposition candidates. With innumerable possible decompositions, the team can not possibly assess them all.[2] The goal here is to apply the philosophy of Pugh [1996] - to identify the desirable attributes of different candidate decompositions and attempt to capture some or all of them in other candidates that will be studied in the same manner. The execution step will reveal a different degree of integrality and integration risk in each concept and candidate decomposition. With this insight, the team can attempt to form additional candidates that combine the desirable architecture and risk attributes of the initial candidates.

The remaining three forms of iteration are discipline specific where each must rationalize their decisions based on the architecture insight. The design team must recognize that, where there is high integration risk, performance projections must be refined; e.g. a high risk, integral chain may force the team to lower performance expectations, while a modular chain may alter assumptions in performance analysis. The KPPs may be altered and some analysis for a candidate will be

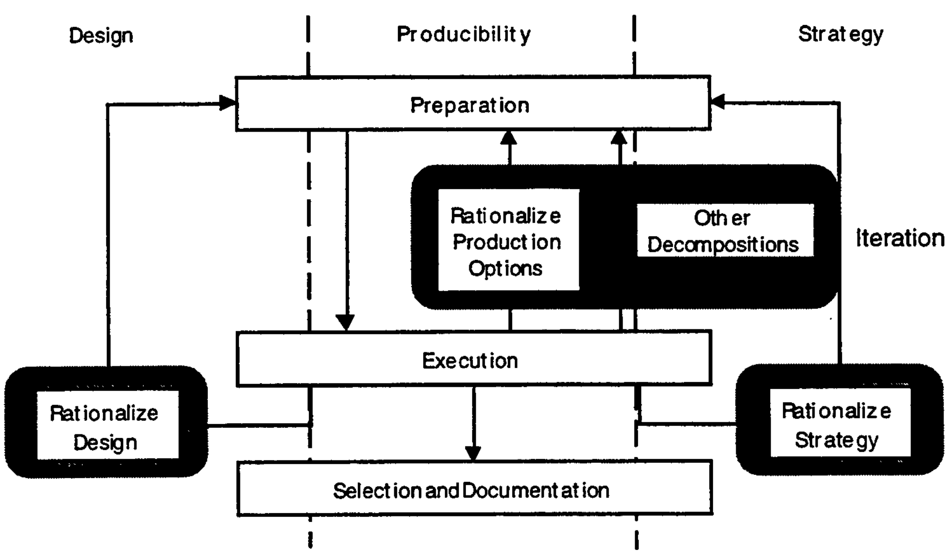


Figure 6-4. The iteration step of the CMM.

[2] This is fundamentally different than assembly sequence analysis of known parts and a known final configuration. In that case a finite number of sequences can be identified because there are specific mates that must be achieved and constraints [e.g. Bourjault, Baldwin et al]. In decomposition there are infinite possibilities, and limited time and resources with which to assess them.

repeated. The producibility group must recognize that integration risk may force different processes to be used and indicate where explicit process control will be needed to overcome the uncertainty that accompanies an integral characteristic. This in turn may alter cycle time and cost projections. The strategy, like the design, must be rationalized based on the architecture insight, so the strategy is properly aligned and implemented, which may cause changes in teaming and supplier assumptions, different priorities among developing technologies, etc.

After each group makes this rationalization, they are prepared to return to the IPT setting for a cross-functional tradeoff among competing objectives with the common basis of chains to guide the discussion.

6.1.4 Step 4: Selection and Documentation

Figure 6-5 shows the fourth step: selection and documentation. Architecture, based on the insight from the CMM, can be a structured criterion for concept and decomposition selection. The documentation of the architecture for subsequent mitigation planning and development phases takes the form discussed in Section 4.6.

6.1.5 The Complete Method

Figure 6-6 combines the four steps into the complete CMM. This builds on the framework established by Fine [1998] for architecture concurrence among the design and supplier chain in two ways. First, it recognizes that the producibility group, based on their influence on the decomposition and role in the chain capture procedure, have a role in architecture analysis that must be combined with design and strategy objectives for the architecture. Second, it provides a

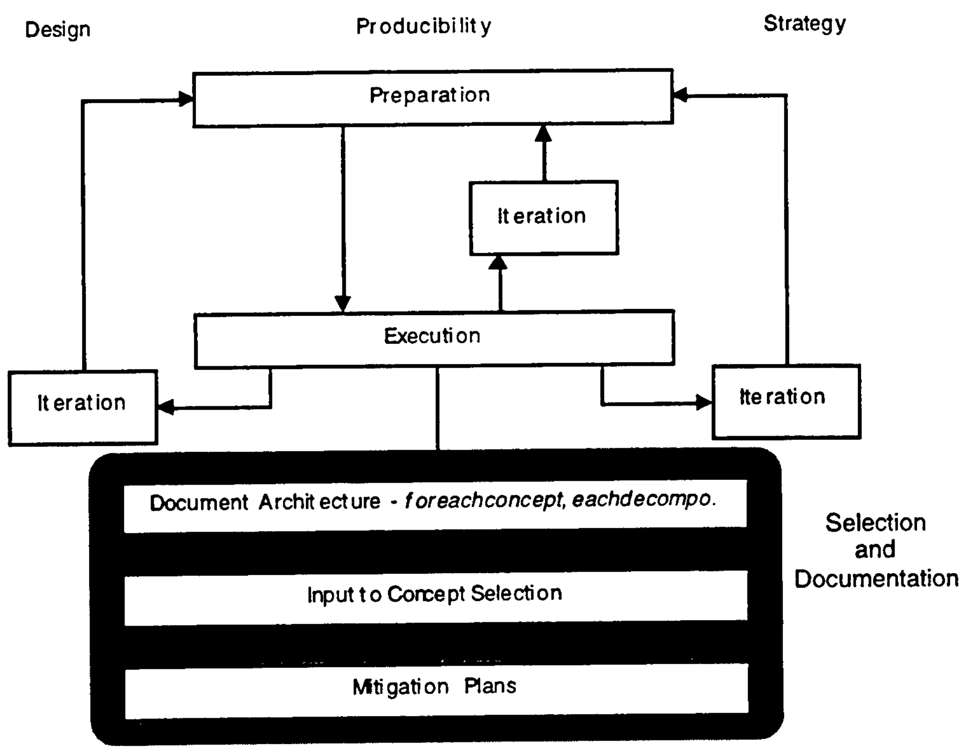


Figure 6-5. The selection and documentation step of the CMM.

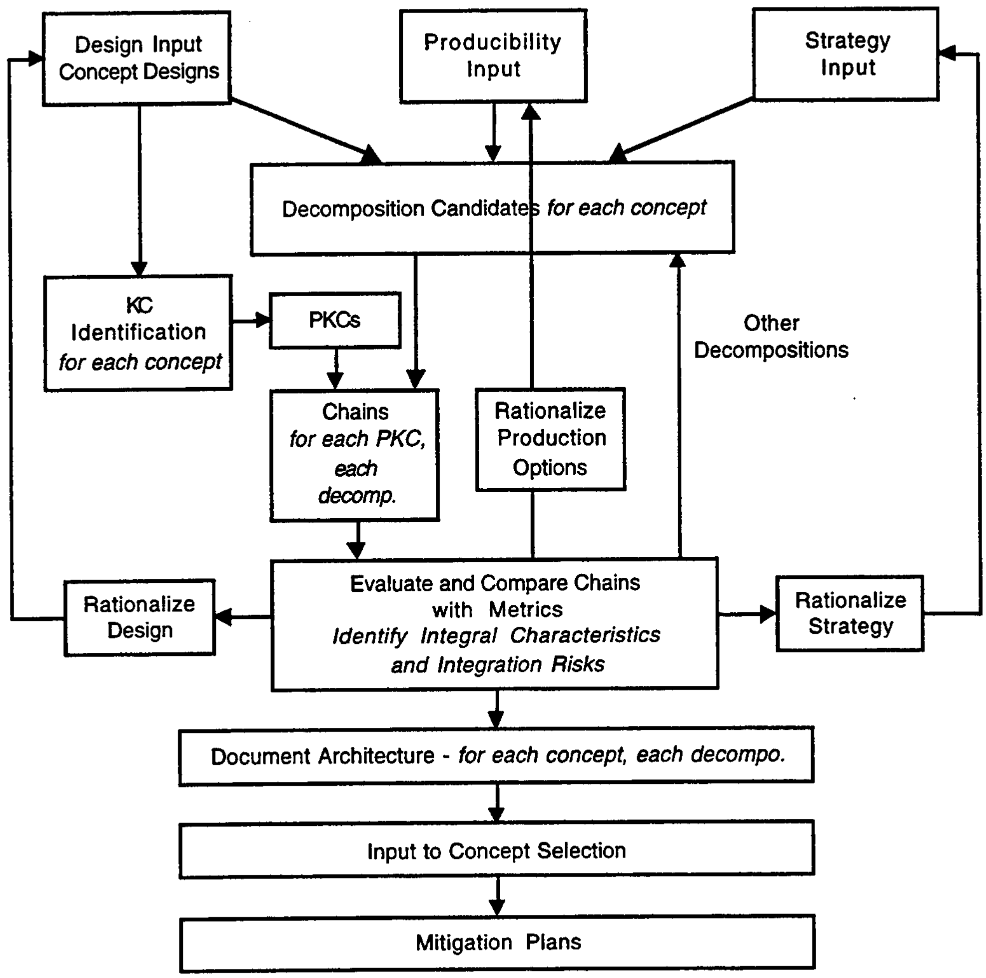


Figure 6-6. The Chain Metrics Method.

set of steps for a cross-functional team to reach the objectives of a common understanding of the architecture, a relation of the architecture to the individual concerns of the different disciplines, and recognition of where these individual concerns conflict.

6.2 Comparison of CMM with Other Design Approaches

This section compares four approaches to developing integral products:

1. architecture analysis during concept design with CMM
2. variation analysis during detail design
3. no variation analysis
4. functional decomposition-driven theories

The four approaches should be compared based on not if, but when, integration issues are revealed during three development phases: concept design, detail design, or production launch. Table 6-1 summarizes this comparison. The CMM reveals the architecture when there is still the most opportunity to affect the outcome with little iteration. Fewer surprises are expected in the downstream phases when compared with the other approaches.

Table 6-1
Comparison of Four Design Approaches

Phase	Approach 1: CMM	Approach 2	Approach 3	Approach 4
Concept design	concepts and decompositions; chains and metrics give feedback for each; result is good architecture, known integration risk	concept and decomposition	concept and decomposition	modular concept and functional decomposition, by definition
Detail design and prototyping	priorities mitigation plans; chains mature in DFC context; variation analysis before detail design; few surprises	detail design variation analysis and tests; surprises as integration risk is discovered; local fixes	detail design tests surprises, no tie to variation analysis; integration risk still largely unrecognized	integration not emphasized if the product is anticipated to be modular; surprises, no tie to variation analysis; integration risk still largely unrecognized
Launch	few surprises; ability to trace symptoms to causes	few surprises; ability to trace symptoms to causes	many surprises; band-aids; quality, cost, schedule suffer	many surprises; band-aids; quality, cost, schedule suffer

Approach 2 alone will avoid many surprises during launch. However, the integration issues are not revealed until sufficient detail is available for a formal quantitative analysis. This is long after concept selection and all high-level decomposition decisions. Iteration is possible, but significant re-design associated with changing the decomposition will result. Consideration of new concepts is prohibitive. Therefore, local fixes are the principle recourse to the detriment of the whole system.

Approach 3 is unacceptable because integration risk is encountered during launch. Approach 4 states that the design should be modular and only functional decomposition should occur. However, in a real product development setting, neither is likely to be completely true, so integration risk will be lurking in launch.

Figure 6-7a shows a summary Design Structure Matrix (DSM)[3] of the approach 3. The red blocks in the upper right of the matrix show that, at the point where integration risk is encountered, there is little recourse to overcome integration risk. Band-aids are the only recourse without substantial cost and schedule penalties. Products developed in this way have poor quality. This is the highest risk approach.

Figure 6-7b shows a summary DSM for approach 2. Here yellow blocks are shown to indicate that more options are available than in approach 3, but the concept is fixed and most options are in the form of local fixes. This presents a higher level of risk than is ideal. Appendix F shows a more complete version of this DSM.

[3] The DSM is introduced in Section 4.4.1.

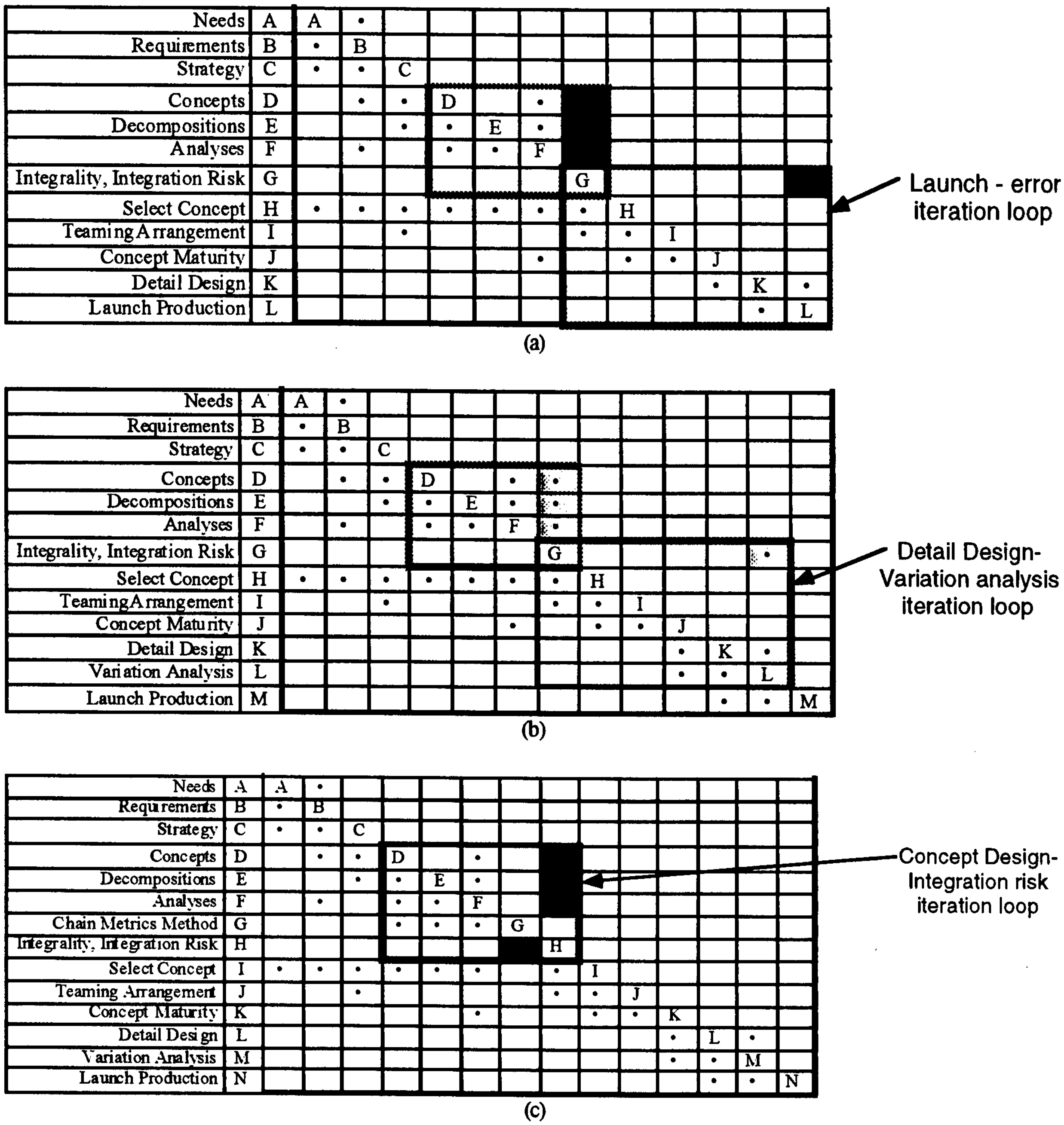


Figure 6-7. Summary DSMs showing the point where integration risk is first encountered in (a) approach 3, (b) approach 2, and (c) approach 1 where the CMM is performed during concept design.

Figure 6-7c shows the case supported by the CMM. Integration risk is encountered during concept design when there is the freedom to alter the course. The green block to the lower left of the diagonal shows that integration risk is something that the team sets out to discover rather than finding it as a consequence of other tasks. The green blocks in the upper right show how the overall development risk is reduced when there is the chance to avoid integration issues that would otherwise be encountered far downstream. Appendix F also shows a more complete DSM for this case.

6.3 Chapter Summary: Architecture Insight with the CMM

The CMM builds an IPT process around chains and the metrics. The method provides a structured process built on the basic framework of architecture and decomposition choices established in Chapters 3 and 4. The full method explains four steps that guide the IPT through the process of achieving architecture insight during concept design when they most control the result. Chapter 7 illustrates this method in the context of a real concept design case study.

7. Illustration of the Chain Metrics Method in the Joint Strike Fighter Case Study

This chapter applies the Chain Metrics Method (CMM) in a real concept design case study. The case study illustrates two aspects of the research:

- how delivery of the inherently integral and conflicting characteristics of a product concept, and the accompanying integration risk, is altered by physical decomposition decisions made during concept design
- how the different resulting architectures *can be* identified through chain analysis in the context of the CMM to coordinate the complex set of decisions and trade-offs made by an IPT involving many disciplines, despite limited design information available during concept design.

The case study is the Joint Strike Fighter (JSF) being developed by Lockheed Martin Tactical Aircraft Systems (LMTAS).[1] Figure 7-1 shows the propulsion system and an outline sketch of

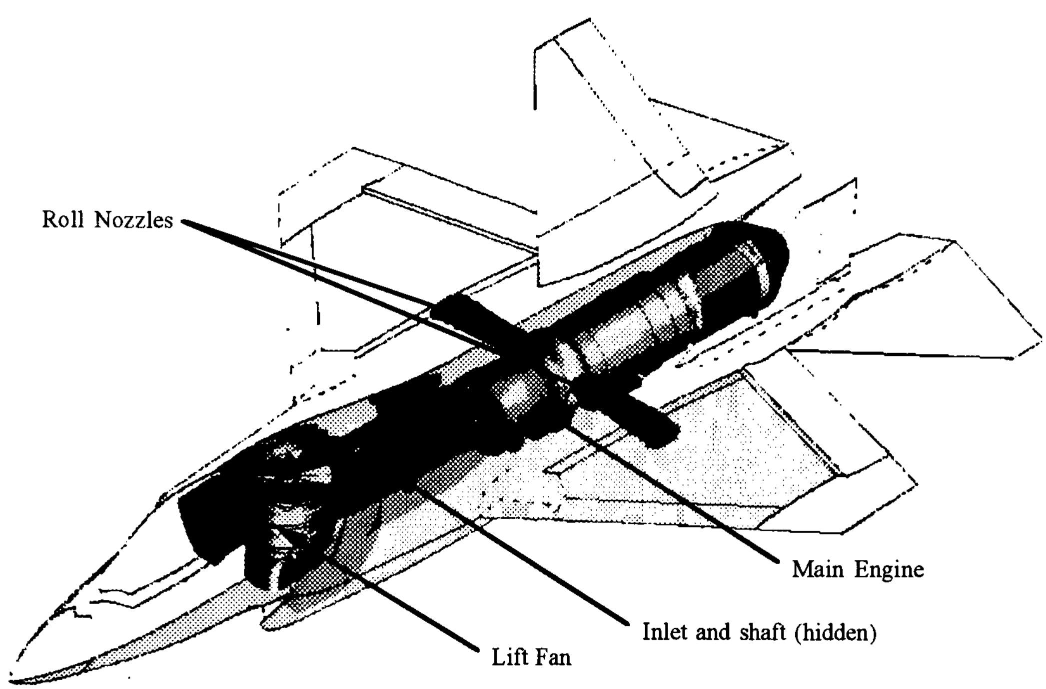


Figure 7-1. The LMTAS JSF propulsion system and outline sketch of the airframe.

[1] Further descriptions of this program can be found in [Ashley] and at http://www.lmtas.com/jsf/jsf.html.

the aircraft, both of which are described in more detail in the next few paragraphs. The JSF is a family of military fighter aircraft, highly integral products that perform many functions in harsh operating conditions. This case study focuses on the development of the "airframe", which is the structural portion of the aircraft that houses the propulsion system and all other systems, protects the pilot, creates the aerodynamic shape, and sustains the flight loads. Figure 7-2 shows the airframe concept pursued in this case study.[2]

The airframe is a platform for many unique variants of aircraft, which presents a unique design challenge for this type of product. The propulsion system is one example of how the variants differ. There is a single "main engine" present on every aircraft version that is fed air by an "inlet." The main engine is used for normal flight. Some variants will also be able to take off and land vertically. Vertical take-off and landing is enabled by a "lift fan" driven by a "shaft" (hidden in the inlet in Figure 7-1) that transfers power from the main engine. In vertical flight, the pilot can roll the aircraft about its long axis with a set of "roll nozzles" that also draw power off the main engine. All of these components are shown in Figure 7-1, and all are housed in the airframe as shown in Figure 7-2.

Figure 7-3 shows a two dimensional schematic of the airframe and propulsion system, which is the view that is used in the remainder of this chapter. The schematic shows the lift fan, shaft, and main engine in gray, and the structural elements illustrated in Figure 7-2. Figure 7-3 also shows two other main categories of variants: those with conventional wings and those with wings that fold.[3] Note that the graphic is asymmetric because it shows one wing for each of these two different variants. Figure 7-3 also shows the coordinate frame for the airframe.

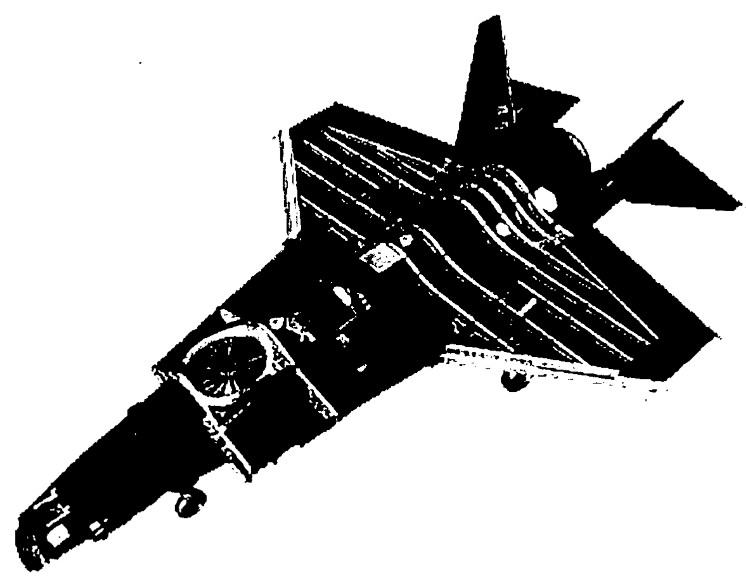


Figure 7-2. The LMTAS JSF airframe concept pursued in-depth in this case study. The airframe houses the propulsion system shown in Figure 7-1, and all other systems while creating the aerodynamic shape and sustaining the flight loads.

[2] Section 7.2.3.2 discusses another airframe concept that LMTAS considered, for comparison.
[3] Of course, any one airplane will have the same wings. I show it this way to emphasize that different variants derived from the same platform must deliver the same KCs.

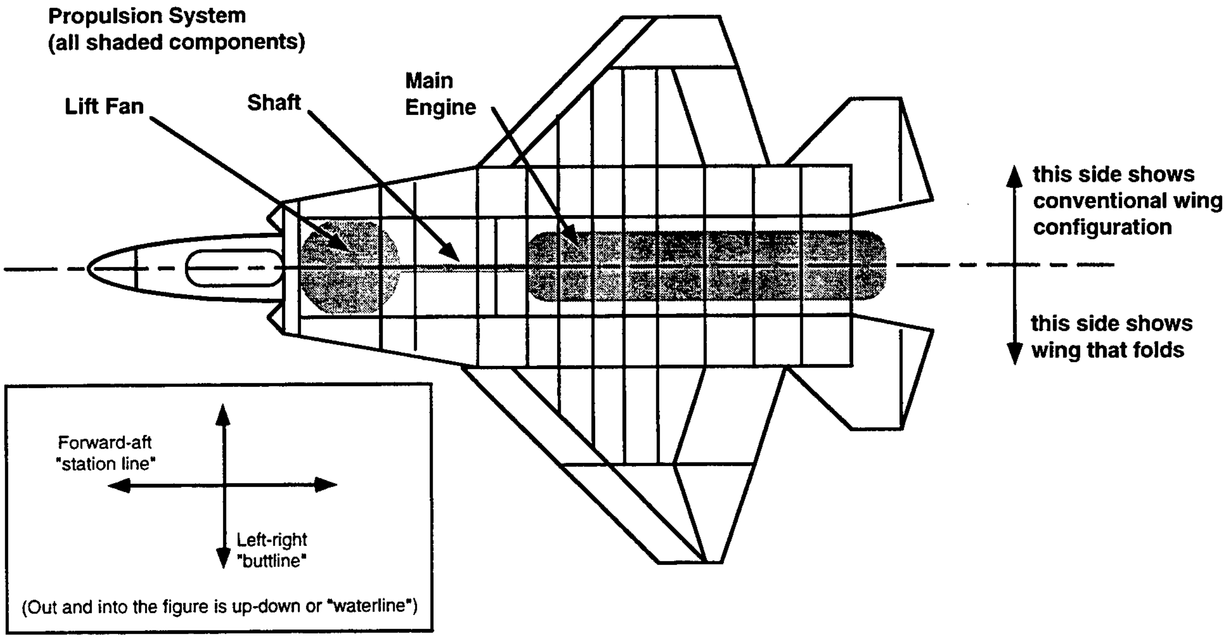


Figure 7-3. LMTAS JSF concept airframe and propulsion system schematic view that will be used in the case study. Note left side shows versions with wings that fold, right side shows conventional wings. The coordinate frame of the aircraft is also shown.

This case study involves competing performance and strategic objectives, where physical decomposition options create unseen conflicts between the two. It therefore creates an ideal environment for testing the CMM. Any technically capable design of this product will exhibit some degree of integrality that will pose some amount of integration risk, both of which will vary depending on the physical decomposition. A fully modular airframe would be a kludge that would never leave the ground, much less perform at the level required of a fighter aircraft. Integrality is required to optimize global performance attributes like load carriage, weight, spatial arrangement of internal systems, and the shape. While the product is integral, the platform strategy, supply chain, and manufacturing system concepts were conceived to maximize manufacturing efficiency to in turn reduce cost. These strategies are most easily applied to modular products, as described in Section 3.3.2.3.3. In addition, these strategic objectives lead to decomposition decisions made in the physical domain. The integral characteristics must be depicted clearly and assessed for conflicts with strategic objectives so that a rational decomposition choice can be made and integration risks can be explicitly documented as the development moves forward.

The case study was performed in an environment indicative of concept design, where no detailed design information was available and the decomposition of the product was incomplete. By applying the method to this type of case, it demonstrates that a qualitative and informative analysis of this problem could be performed with the available, limited information. The structural layout depicted in Figures 7-2 and 7-3 represents the level of design detail available in concept design, though a real layout drawing shows many more of the systems and includes dimensions. LMTAS defines the concept airframe in 3 dimensions, which can be used in conjunction with highly developed CAE analyses that estimate weight distribution, perform

structural analysis, perform computational fluid dynamic analysis, etc. Individual parts are not identified or defined, and not all the structure is represented at this stage. Without a full decomposition and definition of parts, a formal quantitative analysis of how candidate decompositions alter the delivery of the integral characteristics can not be performed.

Figure 7-4 shows a summary of the case study related to steps in the CMM. The first step involves documenting the concept and identifying KCs. The second step involves identifying decomposition options for the concept. The third step involves capturing chains for each PKC in each decomposition using graphical chain representations and Interaction Matrices (IMs). Figure 7-5 shows a side by side comparison of the chains for the PKCs associated with one KC in two different decompositions. Clearly, different decompositions achieve the same function in different physical elements and with varying degree of integrality. Figure 7-6 shows a side by side comparison of the IMs for two decomposition families that, based on the different content of the cells in each matrix, reinforces how the difference in architecture is revealed by chains. The fourth step involves applying the metrics to the chains for each decomposition. Finally, the fifth step involves an aggregate comparison of the decompositions as an input to concept selection. Table 7-1 shows the results of the chain structure metrics scoring, with the KCs scored modular shown in black, applied to three decompositions of the JSF concept called 'B', 'G', and 'I-1'.

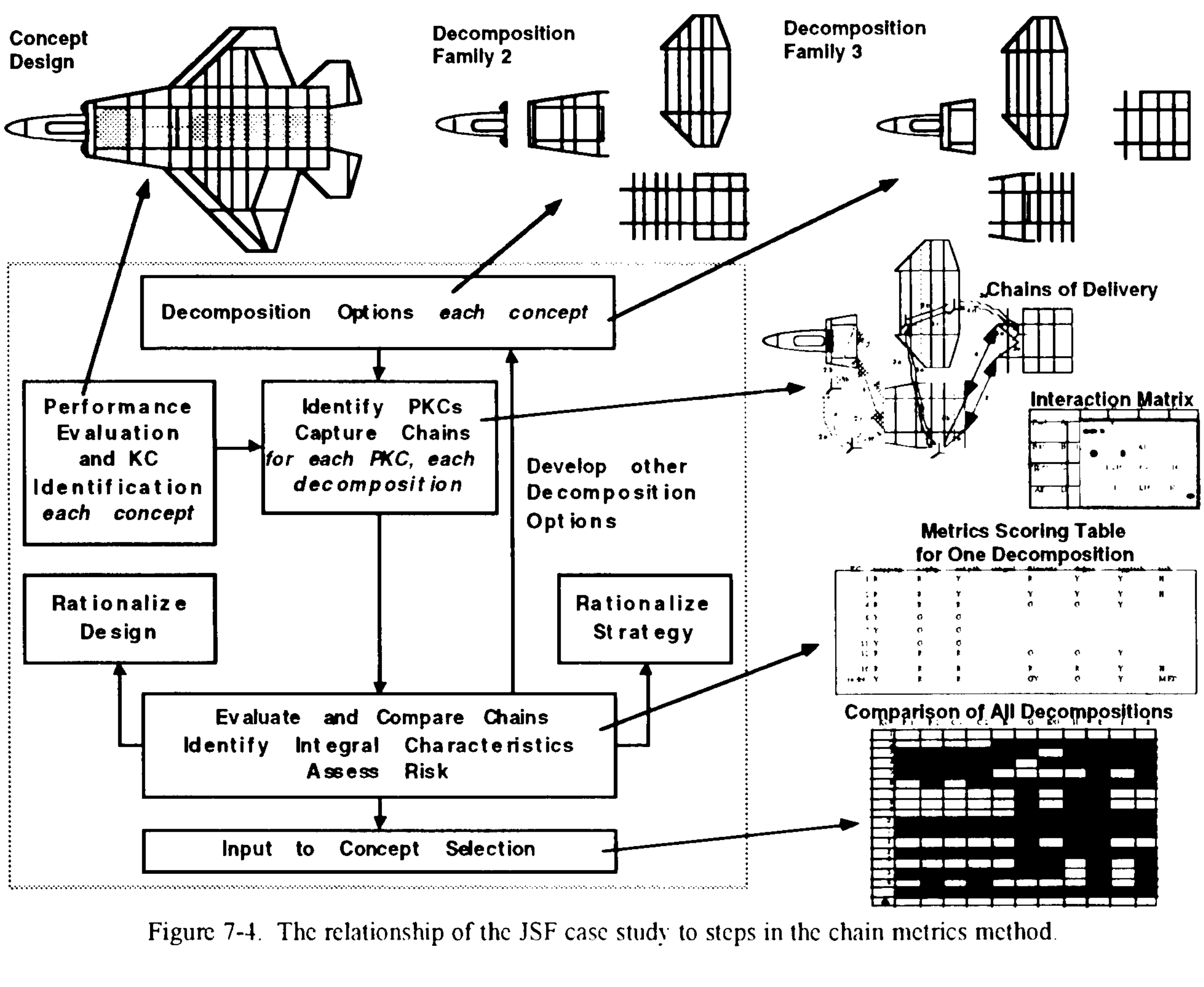


Figure 7-4. The relationship of the JSF case study to steps in the chain metrics method.

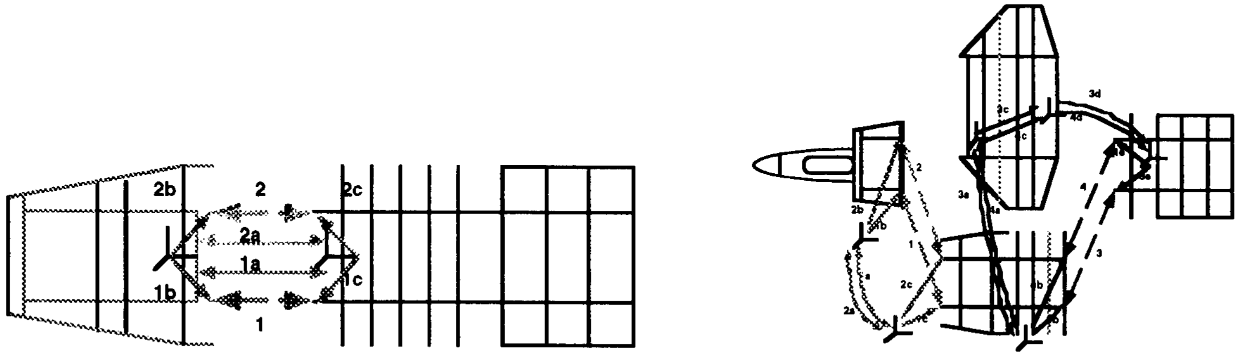


Figure 7-5. Comparison of chains for one KC in two JSF decompositions.

		A	B	C	D
Fwd	A	●			
Mid	B	●	●		4,6,7,11, 12
Upper	C	○	16	8,9	4,12,14
Lower	D	○	1,16	2,16	10,●

		A	B	C	D
Fwd	A	●●●	4,		
Bay	B	1,●○	●	4,12	
Upper	C	○	1,2,16	8,9	14
Aft	D	○	1	1,16	10,●

Figure 7-6. Comparison of Interaction Matrices for two JSF decompositions.

Table 7-2

Summary of the Delivery of 16 KCs in Three Decompositions of the JSF Concept

KC	B	G	I-1
1			
2		■	
3	■		■
4			
5			■
6			■
7			■
8			■
9	■		■
10	■	■	■
11			■
12			
13			
14			
15			
16	■		

Table 7-3

Summary of Integration Risk of 16 KCs in Three Decompositions of the JSF Concept

KC	B	G	I-1
1		■	■
2	■	■	■
3	■		■
4	■		
5		■	■
6		■	■
7		■	■
8		■	■
9	■		■
10	■	■	■
11		■	■
12	■		■
13		■	
14	■	■	
15		■	
16	■	■	■

high integration risk integral KC, yellow represents medium integration risk, and white represents low integration risk.

Table 7-2 shows the same table after the risk metrics have been applied, where red represents a Section 7.1 describes the scope and limitations of the case study, and the vocabulary used to describe unique aspects of the study. Because the product is large and highly complex, a limited

segment of the product was investigated to reflect the complexity while making it possible to achieve the goals of the study. Section 7.2 describes the customer and the company studied in this case. The customer is the DOD representing multiple U.S. military services and those of U.S. allies. LMTAS is one of the competitors for this development, and this section briefly describes recent events that have shaped their strategy, and some of the inherently integral aspects of the concept studied. Section 7.3 demonstrates the CMM in the context of the case study and explains the results for different decompositions. Section 7.4 explains how the architectural insight gained in the study can be used to coordinate trade-offs among the IPT decisions that impact the decomposition. Finally, Section 7.5 summarizes the results in preparation for the assessment and conclusions presented in Chapter 8.

For the reader who is most interested in the application of the method, Sections 7.1 and 7.3 are recommended. Section 7.2 describes the technical, organizational, and strategic issues surrounding the product in detail, but is not required to follow the illustration of the method.

7.1 Case Study Scope and Limitations

Figure 7-7 shows the CMM and highlights the steps presented in this study. This section describes the scope of the study in terms of the KCs investigated, decompositions analyzed, and KC terminology that relates to the decompositions.

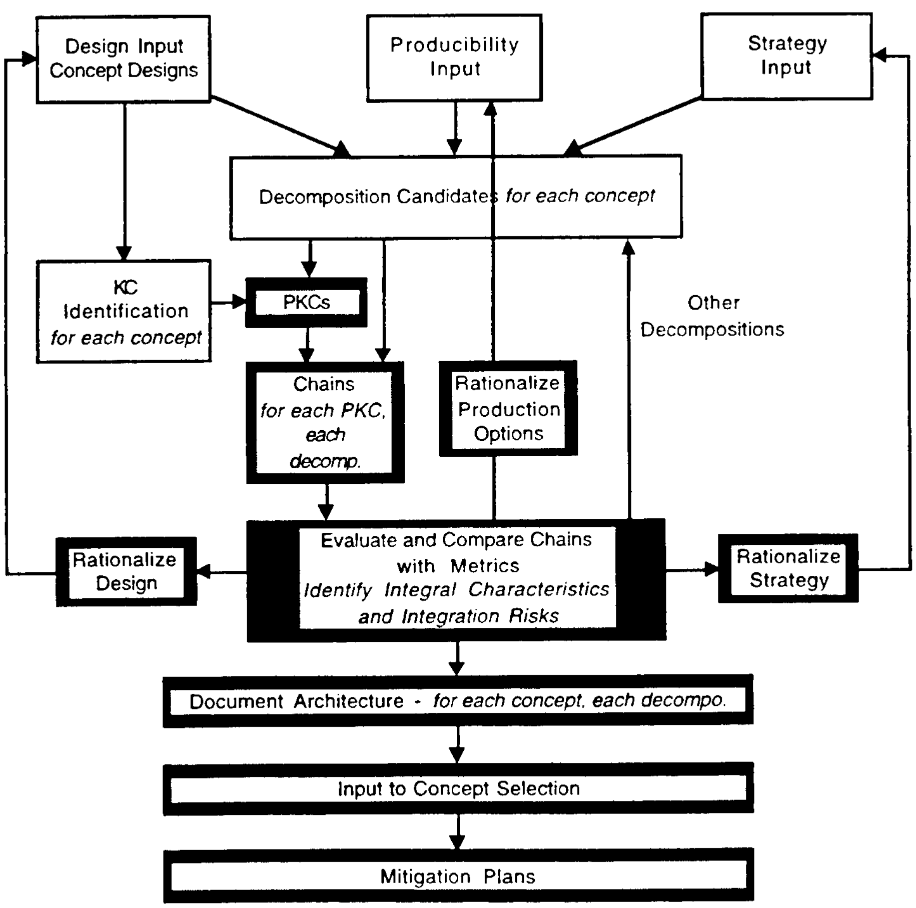


Figure 7-7. The CMM with steps performed in the JSF case study highlighted.

7.1.1 KC Identification

In order to protect the performance capabilities of the LMTAS concept, which is still competing with another company's design as described below, the KCs were not derived from actual KPPs. To indicate KPPs would reveal the actual marginal performance issues of the concept. The KCs selected for this study satisfy two constraints:

- they are representative of real aircraft KCs
- the number is appropriate to represent complex trade-offs while limited to allow the study to be completed.

The 16 KCs selected for the case study fall in four functional categories: structural load carriage, proper function of other systems oriented in or on the airframe (e.g. propulsion, control surfaces that maneuver the aircraft, doors that open and close in flight), conformance to the shape of the aircraft, and interchangeability of components. Not all of these would necessarily be KCs in a real aircraft. For the purpose of the study, these are real geometric attributes that could be difficult to deliver, and therefore warrant chain analysis because they represent real design issues potentially delivered in an integral fashion. The 16 KCs are listed in Section 7.3.

Scope presented a challenge. An important aspect of this study is that many KCs were studied to reveal both integral characteristics and conflicts among the integral characteristics. The exact number is not important, but enough were needed to address the problem at the scope of a real design problem. However, analysis of too many was likely to bog down the study and make it difficult to complete. This dilemma is faced by companies instituting KC programs; how many KCs can be identified before the analysis bogs down?

To scope this study, the KCs were selected in a central portion of the airframe. Figure 7-8 shows the baseline decomposition family[4] provided by LMTAS for this study. The airframe is decomposed on three station lines. "Module 3", highlighted in the figure, was selected as the focus for the case study because it was receiving significant attention in the analyses LMTAS was performing, e.g. assembly cycle time critical path reduction. LMTAS and I selected preliminary, representative KCs in this module and those that crossed over to neighboring modules and other systems. Because module 3 houses the main engine, portions of the weapon bays, wings, etc., there was no shortage of potentially representative KCs. By selecting a set that crossed to other modules and systems, we set up the study to indicate the changes anticipated to be found when different points of decomposition were selected.

7.1.2 Decompositions Studied

There were two distinct types of "breaks" - points where the product is segmented in decomposition - both in the product and in the design team. The first are what I call the "system breaks", which are natural places where the concept is segmented. For example, the propulsion system is distinct from the airframe system because there are discrete connection points envisioned (again, not designed in detail). No matter what airframe decomposition was

[4] I call a set of decompositions that have the same modules a "decomposition family." This is described in more detail below.

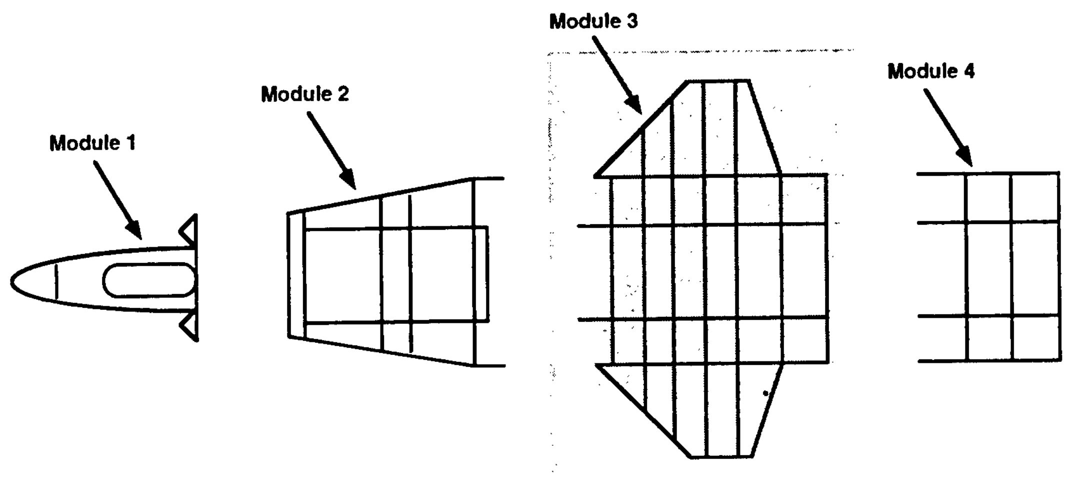


Figure 7-8. Baseline airframe decomposition. KCs were selected that lie in module 3 or are shared between module 3 and other modules and systems.

considered, the propulsion system connects in the same manner. Two other systems[5] were designated as well:

- doors that open and close in flight, which must be connected solely by the hinge lines in the airframe to permit proper motion
- control surfaces that move freely in flight, which also can only be connected at hinge and actuation points

The identification of distinct systems is not based solely on the physical product attribute. Systems are likely to be designed or fabricated, or both, by other companies. Hence there is both a natural physical and organizational boundary between these elements that will be captured in the chain analysis. KCs delivered in more than one system could harbor integration risk.

The next set of breaks are major module breaks of the airframe, like those shown in Figure 7-8. These are loosely defined as the first set of breaks of a system, as the modules will be further decomposed into more sub-elements. In fact there are several candidate decompositions that share the same module breaks, so I use the term "decomposition family" to refer to these related decompositions. Though there can be several options of sub-assembly and component breaks within these modules, it is worth distinguishing a decomposition family for two reasons. First, all decompositions that share the same module breaks will have some portion of the chain structure that is identical, and the differences will only be seen inside the modules. This provides for "economy" in the analysis in that the same steps do not need to be repeated for all decompositions in the family, and if a family fails to look promising then the team can forego detailed analysis of decompositions in the family. Second, LMTAS organizationally dedicated teams of designers, producibility engineers, and various analysts to the module teams, with an overarching team to work on issues of integrating modules. The module teams performed detailed analysis of their modules and considered sub-assembly and component options. The results generated by the module teams were combined into the analysis of the whole airframe. The

[5] There are many systems, these three were found in the KCs we selected. Others would come up in other sets, but the concept of having function shared in different systems is represented.

purpose of module teams is to create reasonable scope for each team to perform its analysis. I broke the chain analysis into stages above the level of modules and within the modules to mimic the task assignments that ware present in the other analyses being conducted by the LMTAS IPT.

I performed the case study on three decomposition families. When the study was initiated, LMTAS provided four decompositions that all shared the baseline module breaks shown in Figure 7-8, which I designated family 1. The consideration of different module breaks, i.e. different families, would create whole other sets of candidate decompositions, but these would each share the identical traits of the family. So the study evolved by considering two other families, first at the module level and then a few decompositions within those modules.

Figure 7-9 shows a hierarchy of the three families studied. The families are numbered 1, 2, and 3, and the decompositions in the families are lettered A, B, etc. In the case of decompositions I and J, they are numbered I-1 and I-2, and J-1 and J-2, for reasons explained in Section 7.3. The highlighted decompositions are the ones that were studied in detail in this case study. The fact that there are four decompositions in each family is coincidence.

Figure 7-10 describes the portion of the analysis performed in each decomposition family. First, I noted which KCs are shared by the airframe and other systems, and which are delivered solely in the airframe. The chains for those KCs that are shared span systems. I recognized what dimensional relationships in the airframe contribute to these shared KCs. I then recognized whether the portion of each chain in the airframe is in one module or several. I then performed detailed analysis of the portion of the airframe branch of each chain that is delivered in module 3

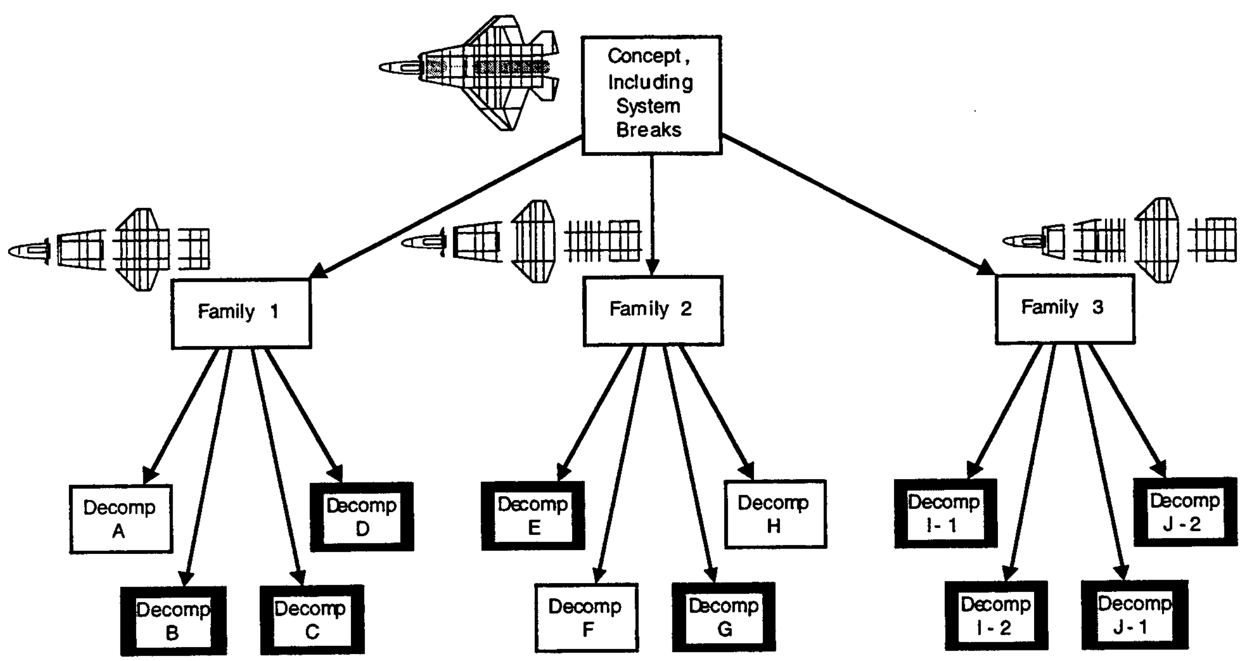


Figure 7-9. Decomposition families studied. Those highlighted are decompositions investigated in this case study.

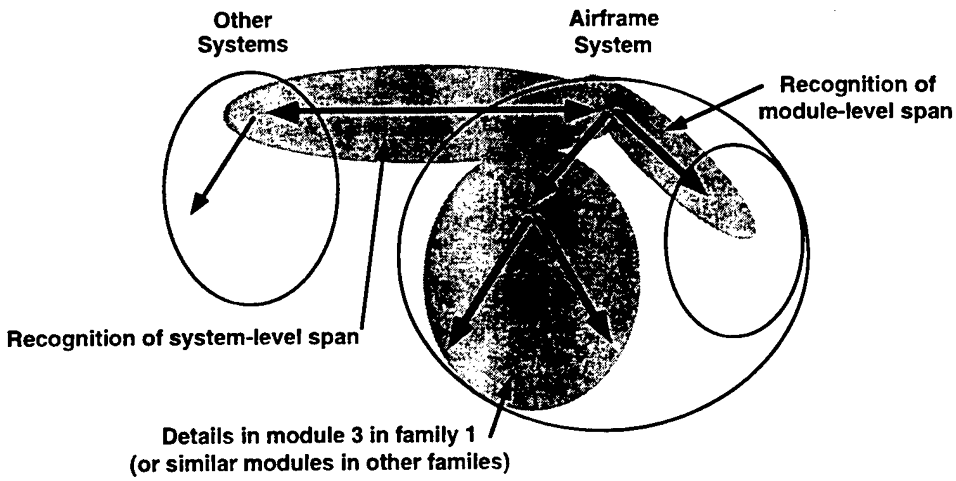


Figure 7-10. Explanation of how the analysis covered links between the airframe and other systems, and portions of the airframe branches in module 3 and similar modules in the other decomposition families.

of decomposition family 1, and in modules that include the portions of module 3 in other decomposition families.

7.1.3 KC Terminology

The above discussion resulted in three levels in the hierarchy in the case study - at the level of systems, at the level of modules in the airframe, and within particular modules. I used these three levels to clarify terminology regarding PKCs. Recall that the discussion in Section 4.1.7.3 stated that some PKCs are common to all decompositions, and others are unique to each decomposition. The following definitions clarify three types of PKCs:

> **System KCs (SKCs) are PKCs in multiple systems that share in the delivery of a KC. As a convention, I define that there cannot be one SKC per KC. There are either zero, or two or more per KC.[6] *SKCs are common to all decompositions of a concept.***
>
> **Module KCs (MKCs) are PKCs that span modules as a result of the first level of decomposition of a system; these MKCs represent the SKC, or the KC in the case where it is delivered in one system. There can be any number of MKCs, zero, one, or more.[7] There will be zero MKCs when the KC or SKC is delivered in one module. When there is only one MKC, it is the same as the KC/SKC. *MKCs are common to all decompositions in a family.***
>
> **PKC is reserved for characteristics in single modules that deliver a SKC, or the KC in the case where it is delivered in one system. *PKCs are unique for each decomposition.***

The reason for naming these KCs is to draw the team's attention to the level of integration required for a KC just by how it is named. If it is called a SKC, the team immediately knows that another system shares in the delivery of the KC. If it is called an MKC, the module team knows that at least one other module shares in the delivery of the KC. If neither name is invoked, the

[6] The purpose of SKCs is to indicate explicitly whether the KC is delivered in one system or many, an important measure of a KC's integrality. Thornton uses the terminology system-level KC, but does not restrict the use to just in the case where multiple systems share in the delivery of a KC.
[7] For example, more than one MKC can result if an element like a structural member whose alignment is critical is broken into 3 pieces by module choices; there will be two MKCs, one at each joint of modules. I find this in the keel beams of the JSF, an example discussed in Section 3.2.

team knows that its module completely delivers the KC. Section 7.3.1 describes a corresponding numbering system that tags the KC by its type, allowing for recognition of the category of KC (described in Section 4.3.1.1) just by looking at its number.

Each KC should be translated into at least one SKC, MKC, or PKC, even if that involves renaming the KC. The rationale for this will be apparent in Section 7.3.

7.2 LMTAS Joint Strike Fighter Program Overview

This section provides background on the JSF program to establish the strategic issues and competitive environment. I begin with a description of the government's goal of creating a low cost fighter aircraft, and then discuss the LMTAS approach. To further emphasize how important it is that this step be conducted during concept design, I explain below why low risk is important in this case study but how technical and strategic conflicts that lead to integration risk are likely. The government requires the competitors to rationalize risk in their proposed development approach so cost, performance, and schedule can be accurately predicted. Based on its experiences described below, LMTAS positions itself in this competition as having a low risk approach. LMTAS expects its experience in fighter aircraft development, and active risk management methods, to be a strong competitive point in its proposal to the government. For LMTAS, it is critical not only to recognize the architectural conflicts, but also to assess the integration risk and demonstrate that mitigation plans are in place to reduce this risk. By the end of Section 7.2, the reader should be convinced that in a complex problem such as this, a systematic approach to the problem is required, such as that posed in the CMM.

7.2.1 Government Approach for an Affordable Platform Fighter Aircraft

Defense product development programs are managed by a "program office" that serves as the purchaser for the "user" and from the "contractor." The user is the military organization that employs the weapon; they do not buy their own weapons. They establish the needs for the new product and communicate with the program office on the development of the physical design solution. The contractor is a company that is under contract with the government to develop the product. In the case where the program office is buying a product for more than one branch of the military, it is called a "joint program office" or JPO (pronounced "jay-poe").

An analogy between the JSF JPO and a car company may be useful to those unfamiliar with government product development. A major car company has groups that develop its products, such as Ford's Light Truck Division. These groups require approval of their designs at certain milestones by an internal authority that determines whether the design is proceeding properly, i.e. it will satisfy the needs that marketing has identified, is financially and technically sound, etc. In this case the approval authority is in a position similar to that of the JPO. The JPO does not design the system, their mission is to ensure that the needs will be satisfied by the design that is proposed.

The JSF is indicative of the challenge faced by the government in all current defense product development activities: learning to place equal emphasis on cost and technical performance. Just as firms in many commercial industries have faced international competition that has led them to

reform product development, different pressures on the government have resulted in the same product development challenge. Prior to the end of the Cold War, defense budgets were sufficiently large enough that system cost was not equally emphasized with technical performance. The focus for decades has primarily been on performance, which has resulted in extensive means for making performance trade-offs during concept design. Now cost is of paramount importance because defense budgets are severely constrained and likely to decrease further. In products as complex as military fighter aircraft, cost-performance trade-offs are quite complicated. As discussed in Section 3.3.1.1, we recognize that most of the cost of the system is committed in concept design, yet there is weak and fragmented information with which to make cost assessments during that phase.

The following describes one part of the JSF JPO's approach to developing a product that meets or exceeds a challenging cost target while achieving superior performance. The focus here is on the platform strategy. Appendix B, a review of DFMA tools, includes a section on producibility analysis tools developed by the JSF JPO.

7.2.1.1 Program History and Schedule

Figure 7-11 relates the JSF history and schedule to the phases of defense product development discussed in Section 3.3.1.2. JSF started as an office whose mission was to serve as the central guidance for development of technologies that were candidates for the development of new low-cost "strike" aircraft.[8] JSF then began development of the aircraft in the concept phase in late 1993. Three contractors competed in this phase: Boeing, LMTAS, and McDonnell-Douglas. In 1996, Boeing and LMTAS were selected for the "concept demonstration phase", where prototype aircraft are being built and important manufacturing processes are being tested. Concept demonstration culminates with the flying of prototypes in 1999, after which one contractor will be selected to develop a detailed design and production system with goal of initial production late next decade.

7.2.1.2 Platform Strategy that Requires a High Degree of Commonality

The JSF JPO's strategy is to develop a platform airframe from which a variety of aircraft variants can be developed. This strategy is representative of many commercial products, from

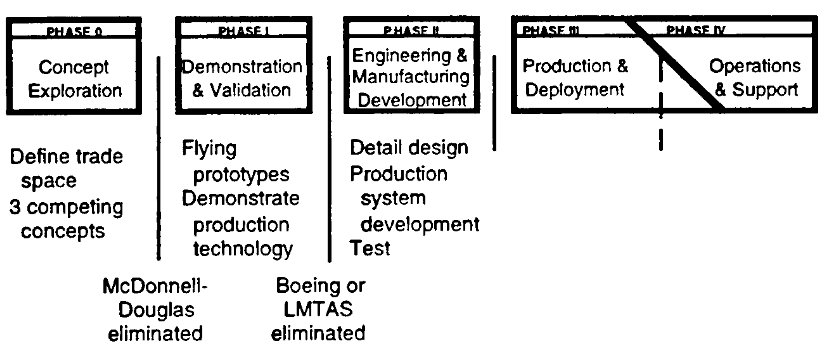


Figure 7-11. Timeline of JSF phases relative to Figure 3-12, and content of those phases.

[8] Strike aircraft are small, maneuverable aircraft whose principle mission is to attack ground targets, as opposed to large bombers that attack ground targets or small aircraft that attack other aircraft.

automobiles to power tools to consumer electronics and on and on. One contractor will be selected to develop the platform and all the variants.

Clearly, architecture is at the heart of this problem. In order to optimize weight and flight characteristics, aircraft designs are highly refined, so every piece of structure is designed to best carry loads but to weigh a minimum amount. They are integral designs that involve function sharing. Because many of these functions conflict, coupled integral characteristics across many variants of the product must be managed. The product lies in the right hand side of the matrix of architecture choices discussed previously. Modular designs, as discussed in the examples of Chapter 3, result in kludges that will not fly. The platform strategy seeks to maximize the number of common parts while minimizing the impact on performance. This is a modular approach. The optimum solution will have to achieve a delicate balance. It is the contractors' job to pose solutions. The solutions will be judged by the JPO against a set of criteria that mainly involve fixed cost targets for each variant, performance thresholds (minimum performance on certain measures derived from the missions that the aircraft will have to perform) and global measures of "commonality": the amount of common components in each variant.

These variants cover quite an extensive range. At one end of the spectrum is a small aircraft that can take off and land *vertically* but fly normally in all other portions of the flight. The capabilities of this variant will be included in some or all the aircraft for several customers. Vertical flight requires that a propulsion system be able to create thrust down, while normal flight requires thrust back, as shown in Figure 7-12. Two major technical issues associated with vertical flight are weight and the concept for generating vertical thrust. Weight is a significant constraint because, unlike horizontal flight where all lift is created by aerodynamics, all lift during vertical flight must be generated by the power of the engine converted to vertical thrust. This expends vast amounts of fuel, creates heat, and must be achieved by an engine that can only take up a limited space. The concept itself can vary greatly. Thrust can be vectored downward through nozzles off the main engine, or by a fan that is in principle just like the regular jet engine only oriented vertically. In either case the temperature of the gas propelled from the engines is critical. Unlike the case of the conventional jet engine that propels hot gas back into the atmosphere, in vertical flight this hot gas is directed down onto the surface. It is so hot it could literally melt the ground below.

At the other end of the spectrum is a conventional aircraft that operates off aircraft carriers, which will be used by the U.S. Navy. The technical issue here is the short landing distance,

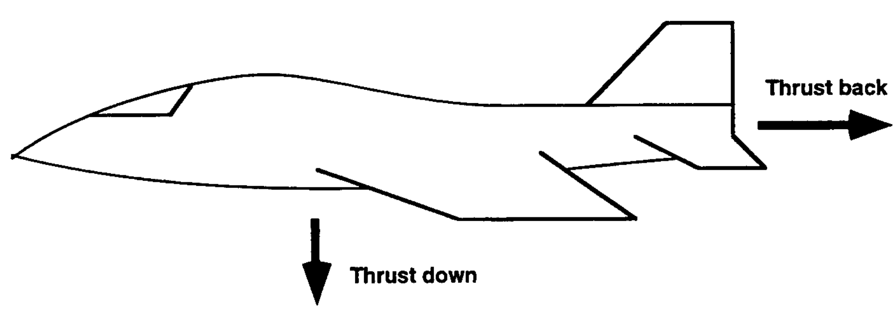


Figure 7-12. The version requiring vertical flight must generate thrust down and back.

which creates two problems. First, in order to diminish the kinetic energy of the aircraft and stop it, the aircraft hits the deck of the ship very hard. These are not smooth landings like in an airliner. Much of the energy is absorbed by hitting the deck vertically, which creates huge impact loads in the aircraft structure. This requires larger structural members than in aircraft that land on runways, so they weigh more. The heavier structure may have to be made of different material, such as titanium instead of an aluminum alloy. The second issue is the speed at which the aircraft approaches. The aircraft approaches at slower speed than other fighter aircraft to reduce the energy. Slow speed, with landing gear down, at low altitude is an extremely dangerous flight condition and is where the vast majority of air accidents occur. A very slight drop in air speed over the wings can cause a stall condition where lift is lost, and with little altitude there is unlikely to be time to recover. To fly at low speeds the aircraft usually needs larger wings and has to be highly maneuverable in this configuration. This requires carefully designed wing shapes and control surfaces. As described below, in order for this variant to perform properly while fitting in as a member of a platform, the wing design can not be fully optimized. One additional related problem is that space on an aircraft carrier is limited, so the aircraft need to be parked close together. This requires the wings to be folded, on top of all the other requirements, so they take up less space when the aircraft is parked. This adds additional weight and alters shared elements of the wing in members of the platform that do not have folding wings.

Somewhere in the middle of this spectrum are aircraft for conventional fighter aircraft operations, like those used by the U.S. Air Force and many of our allies. Here the technical challenges are to maximize range and maneuverability in flight to make the aircraft most effective in its missions.

This set of variants represents an extremely difficult architecture trade-off. To satisfy all three sets of requirements, tailored integral designs are needed that maximize the critical performance issues of each while attempting to do so with some percent of common components. The contractor must prove that it can develop the platform with minimum risk, which includes integration risk indicated by conflicts between the technical and strategic objectives.

7.2.2 Lockheed Martin Tactical Aircraft Systems approach

The following describes the LMTAS approach to the JSF design problem. First, a brief recent history of LMTAS explains their corporate strategy and low risk tendencies. I then describe their approach to JSF in terms of the design organization, strategy, and their internal approach to measuring risk. Next, I then introduce aspects of their selected concept and one other that they considered.

7.2.2.1 Lockheed Martin from 1991-1994

LMTAS' JSF strategy reflects their history as an organization, their past products, and their recent applications of the tenets of lean manufacturing. I judge this history as neither good nor bad for their potential success on JSF, but feel it reflects much about their approach and is worth a brief review. In the course of my interactions with LMTAS, I gained the following insights:

- LMTAS, in response to two major set-backs discussed below, has worked very hard to reform its image and now positions itself as a low-risk developer and efficient producer of aircraft.
- Because the F-16 is its signature product, most of LMTAS' JSF team has experience with that product; this tends to bias their judgment toward that experience. This is neither good nor bad, but it can confine creativity along the lines described by Henderson and Clark [1990].
- LMTAS has a wide set of options for investing in new processes for the JSF following a large-scale effort to outsource many fabrication technologies.

LMTAS has a long history but its most recent roots are as the military fighter aircraft group of General Dynamics Corporation (GD). Mergers are common in the current defense industry environment, so it is not surprising that LMTAS was purchased by Lockheed, now Lockheed Martin, in the early 1990s. In the mid-1970s, GD had won the development of the F-16, a small, highly agile multi-role fighter that has been produced in the thousands, a very large number for aircraft, and numerous variants. LMTAS has basically remained in steady, albeit fluctuating production of the F-16 ever since with little other production work. The F-16 is the signature product of the firm: an agile, versatile product that has been produced in large numbers and several variants, and in recent years at low cost.

In the late 1980s and early 1990s, GD was shaken by two major set-backs. First, GD was a partner with MDA on the failed development of the A-12 stealth aircraft for the Navy. The program was canceled in the detail design phase. The reason for the failure, a combination of requirements creep and cost escalation, remains a point of contention but continues to equally affect Government procurement and the industry. Second, by the early 1990s, LMTAS lost strict control of the numerous F-16 variants in production. The problem reached the point where the Air Force threatened to withhold progress payments and refuse delivery. Interruption of the firm's signature program, and at the time its only significant production program, would have threatened the business. LMTAS responded successfully, but this was achieved in marked departure from their traditional practices. LMTAS went from a vertically integrated company that could make nearly every part of the F-16 in the same plant in which it is assembled to a position of near rampant outsourcing to the degree that there are only a few fabrication capabilities at LMTAS.

Since then, LMTAS has been highly successful in product development considering the major lull experienced in the industry. Recently, LMTAS has played a central role in the design and initial production of two fighter aircraft where they teamed with other companies. These programs modernized LMTAS' product development tool set; for example 3D CAD was utilized, so a large portion of their design group gained experience with CATIA in that program. An additional product development program is currently underway. In the course of the recent programs, LMTAS has developed fabrication and processing capabilities for composite parts, and extensive experience in designing products appropriate for manufacture and assembly with these materials.

LMTAS has to prove two things to the JPO: that they can lead this platform development program with low risk, and that they have a well conceived strategy for investing in or outsourcing the key technologies and implementing them in the product. The ability to recognize integration issues and integration risk, and to develop plans to mitigate this risk, is central to LMTAS' strategy that has evolved from their culture. This strategy is straightforward: they consider their core competencies to be aircraft integration, airframe assembly, and composite fabrication and processing, which is the role they will play as the JSF lead, and have proven they can work in a dispersed supply organization as a team.

7.2.2.2 JSF Organization

As aircraft integrator and airframe assembler, LMTAS must be able to identify physical elements that are suitable for outsourcing and understand the integration issues. LMTAS will team with several other major companies (maybe even Boeing if the JPO asks). A team approach may represent a choice, or a response to outside pressures. Many products in many industries are developed in teams of firms in order to share the up front risk, though this approach requires integration. This approach is also driven by several domestic and international factors related to the low defense budgets but the need to sustain the aircraft industry development capability. It has been recognized from the outset that the JSF will be developed and produced in a dispersed supply chain but must come together as a highly integrated system. Some team members, such as the engine contractors, are dictated by the government.[9]

Some in the aircraft industry would debate whether management of such a dispersed team is in fact an issue.[10] I feel that a complete view of this problem shows that this and other industries have yet to master such challenges. Two recent successful programs[11] are worth noting because the applicability of their success to JSF should be qualified. For example, the recent F/A-18 E/F fighter is built in such an arrangement and has had a reportedly smooth assembly process attributable to an IPD approach, extensive variation analysis of assemblies, and DFMA during detail design. However, this is the third generation of the same product, where decomposition and concept design were not debated, so it is not a direct analogy to a new design problem like JSF. The F-22 recently also started initial production (five were in production as of this writing) in a team environment. A well conceived IPD approach again led to a smooth initial assembly process. However, cost, and the resulting requirements for manufacturing efficiency, were not a major driver on that program. Because the assembly process for JSF will have to be greatly more efficient and faster than that for the F-22 in order to reach the cost goals, assembly integration can not be taken as a given to be as smooth. Our project experience from other relevant aircraft programs, such as the Boeing 777, shows that initial success in assembly is indicative of substantial progress due to IPD, 3D CAD, DFMA, etc., but many integration issues still linger in these programs that are found downstream in production. I expect similar issues to show up in the F-22 that will prove that JSF must continue to emphasize integration. As a final note, JSF is a unique challenge when compared with any of these programs because none of the above were a

[9] The active role played by the Government in architecture and integration risk is discussed in Section 8.4.1.2.
[10] I have participated in this debate in both my own research and through dialogue in the Lean Aircraft Initiative forum.
[11] I have attained an introduction to each of these programs through. among others. the meetings and discussions listed in Appendix A.

platform development problem, nor did they have the extensive international influence of the JSF.

LMTAS will also create a dispersed supply chain for the JSF that will require explicit attention to the integrality of the elements selected for outsourcing. LMTAS will perform the role of final integration, final assembly of the airframe, and at most assembly of *one module of the airframe*. Design and production of the other modules will be led by a partner company. Widespread outsourcing of sub-assemblies, components, and parts is also likely, though some specific manufacturing capabilities and parts will be kept by LMTAS.

7.2.2.3 Strategic Influences

Two other strategic influences impact integration issues and integration risk: assembly cycle time and investments in fabrication technologies. Assembly cycle time reduction is an emphasis in all segments of the aircraft industry.[12] Cycle time reduction in assembly is expected to make the industry less affected by fluctuating demand, more responsive to the customer, and effective at reducing cost. Cycle time reduction is enabled by two approaches: more detail is pushed into fabrication (such as unitization of parts), and the airframe is decomposed into more, smaller modules, sub-assemblies, etc. so more work can be performed in parallel and therefore off the critical path.[13] These two approaches have direct influence on the physical decomposition, and hence chains, and hence architecture and integration risk.

The second major strategy requires the identification of fabrication technologies in which LMTAS should invest for both development and capacity. LMTAS recognizes the issues of dependency and outsourcing, and with their recent history of outsourcing many fabrication capabilities, has a diverse set of options for this investment strategy. LMTAS has performed a well conceived knowledge gathering process of new capabilities that can enhance their design and contribute to cost reduction. The issues that remain are the choice of processes in which to invest, and the selection of parts for these processes.

7.2.2.4 Integration with Existing Risk Management

The integration risk identified in the conduct of the CMM would integrate with the LMTAS risk detection and management approach,.which is already a well conceived, structured methodology. The CMM would specifically add integration risk related to the KC delivery to an extensive group of risk analyses that the IPT is utilizing on JSF. The existing risk approach also integrates LMTAS' mitigation plans with specific integration issues being addressed in the development plan. The integration risk insight would therefore integrate smoothly into the existing management tools.

[12] Both Boeing and Airbus hope to achieve aggressive - as much as 50 percent - assembly cycle time reduction goals for their commercial aircraft production programs.

[13] The latter approach intersects with the outsourcing problem, because by having more elements, there is more to outsource to more team members.

7.2.3 Design Drivers

Three major design decisions made by LMTAS have impact on the CMM case study. The following briefly describes each, and then combines these design decisions with the keel alignment and weapon bay door alignment problems discussed in Chapter 3 to depict the inherent integrality of the concept.

7.2.3.1 Propulsion System

The first major design decision is the choice of propulsion system. As discussed above, the propulsion system must enable both vertical take-off and landing and normal flight. LMTAS selected what should be characterized as an integral approach, called the "shaft-driven lift fan." In this concept, as depicted in Figure 7-1, the main engine, a normal jet engine, transmits power through a shaft and gear box to a vertically oriented lift fan. The lift fan and a movable nozzle on the main engine combine to create vertical thrust.

The advantages of this system are:

1. the lift fan exhaust is cool, so there is no risk of hot exhaust harming the aircraft, ground crew, or landing area[14]
2. there is one fuel system, so weight decreases
3. the platform concept is simple, the only unique components are the lift fan, nozzles, and shaft; when they are not present, there is an additional fuel tank in the space taken by the lift fan.

Three propulsion system design issues result, and each involves dimensional alignment in the airframe:

1. The main engine must be properly aligned in the airframe to properly vector the thrust horizontally and transmit the torques into the airframe, a requirement that is common to all jet aircraft.
2. The shaft must be aligned between the main engine and lift fan to properly transmit power and minimize wear in bearings and gears; this is achieved by proper alignment of the lift fan relative to the main engine by the airframe.
3. The roll nozzles must be properly aligned to ensure proper control as the pilot lifts (or descends) and transitions between vertical and horizontal thrust, which is a highly dangerous portion of flight.

These are all inherently integral characteristics because they are distributed throughout the airframe and function is shared in many elements. Recall the discussion of the integral nature of the weapon bay, that dedicated elements for aligning hinges, supporting the weapons, etc. could not be included because the airframe would in the end be a kludge of numerous such elements. The propulsion system extends this argument. The alignment of the lift fan and main engine to attain shaft alignment can not be achieved in a single element of the airframe, because the requirement is so widely distributed that the "shaft alignment element" would in fact be most of the airframe! The same challenge is also faced in the other two alignment requirements. It may

[14] The main engine exhaust is hot, but is at the rear of the aircraft and away from the crew.

not be possible to align the main engine in one airframe element, and it may not be possible to align the roll nozzles in one element. Further, any of these that are not contained in one element may conflict with other alignment requirements that are "cut" at the same boundaries. An alternative that uses a dedicated lift engine, fuel system, and controls is inferior technically because it is heavier, more bulky, and less efficient, and creates more heat. However, it would be relatively modular because all the components that affect vertical flight would be dedicated to that one function and located near each other.

The design issues associated with this propulsion system exemplify how technical requirements lead to integrality.

7.2.3.2 Airframe Layout

The second major decision was the choice of airframe layout. LMTAS investigated several concepts. Figure 7-13 shows a "delta/canard" concept that is fundamentally different than the wing/tail concept. This concept has larger wings, and has canards forward of the wings that affect climb and descent in normal flight. The concept is shown with the same propulsion system as that described above.

The airframe layout concept selection was based mainly on flight characteristics, as modeled in CAE tools and physical wind tunnel prototypes. However, there are also two main distinctions in the architecture compared to the wing/tail concept that should be noted:

- the change in layout alters the spatial arrangement of systems and potential decomposition candidates, and hence which alignment problems will be coupled and conflict; e.g. the weapon bays would potentially be located in a completely different region, and may not conflict with the keel alignment and propulsion alignments the way it does with some decompositions of the selected concept.
- the change alters how the wings interact with the structure, and hence completely changes how loads are carried, and hence leads to different KCs.

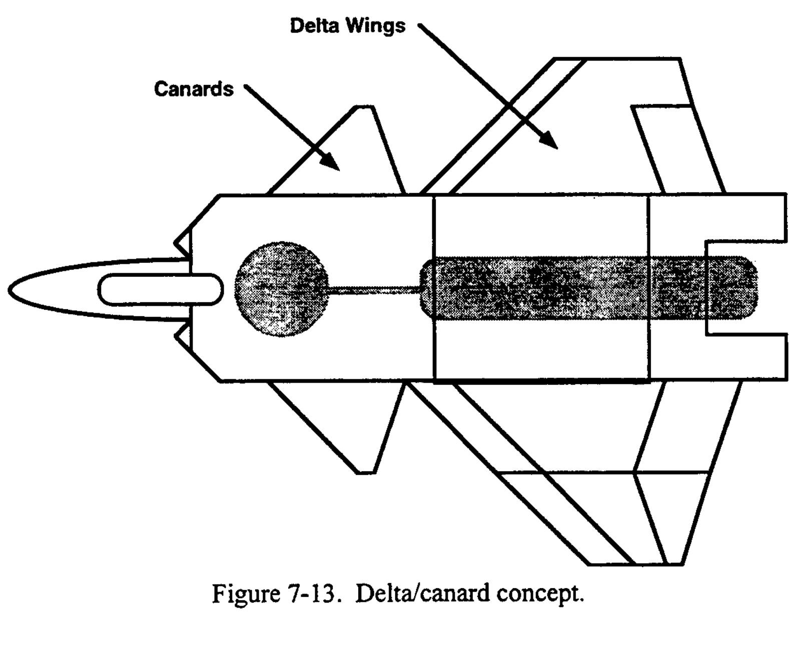


Figure 7-13. Delta/canard concept.

Because each concept has different KCs and candidate decompositions, each has a different architecture that includes a different degree of integration risk. The choice of airframe was neither fully a technical nor strategy decision, but one that satisfied some objectives of each.

7.2.3.3 Example of Commonality in the Platform: Wing Shape

The third major choice involved balancing the performance of each individual variant of the aircraft with the amount of components common to all variants. To maximize performance, each variant would have an optimized wing shape. But to maximize the cost and flexibility benefits of the platform strategy, all would have identical wings.

LMTAS selected a balance of these two extremes with a common wing box but tailored control surfaces for each variant, as shown in Figure 7-14. The wing box is the same shape for each variant and different control surfaces are used for the larger Navy wing, which includes hinged wing folds as shown in Figure 7-14a, and smaller Air Force wing, which includes fixed wing "tips" as shown in Figure 7-14b.

This approach is a compromise and indicative of conflicting pressures for integral and modular architecture. The performance is reduced relative to a design with an optimized wing for each variant. A simple description was described to me as the following. A larger wing, like the Navy version, would have both a larger plan view, as indicated by the larger control surfaces in Figure 7-14a, *and* a larger cord height, as shown in Figure 7-15a. The smaller wing would be smaller in both views. However, in order to have the same wing box, the wings have the same cord height, as shown by the common compromised wing box in Figure 7-15a. The result is that shape is compromised for both, as shown in Figures 7-15b and c, and along with it the flight performance.

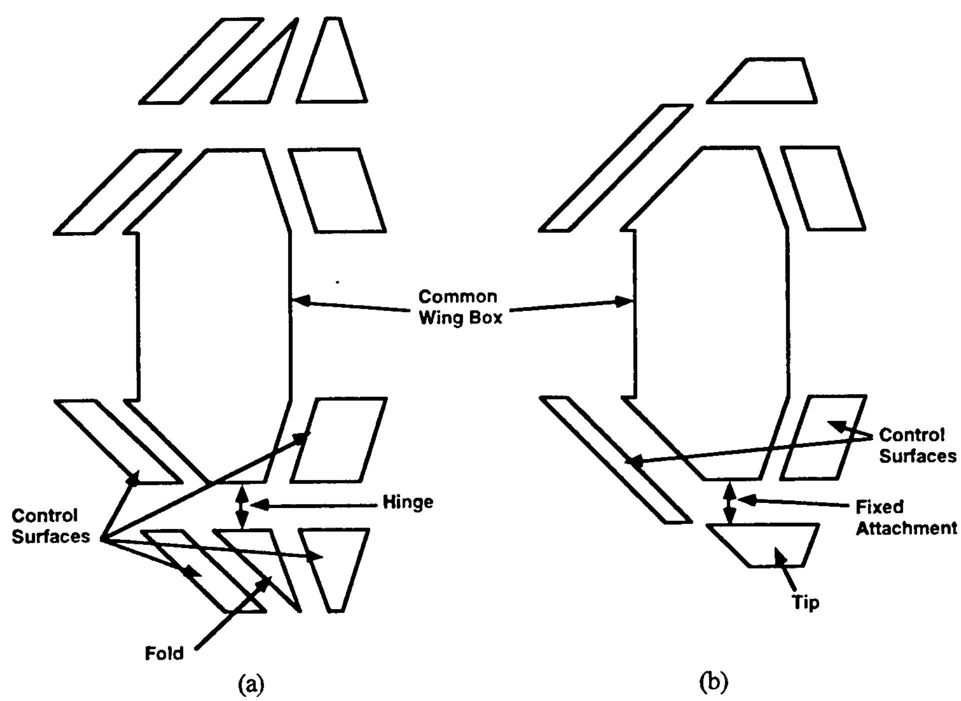


Figure 7-14. Wing design balancing competing objectives: common wing boxed with dedicated control surfaces for the (a) Navy variant with folds and (b) Air Force variant with tips.

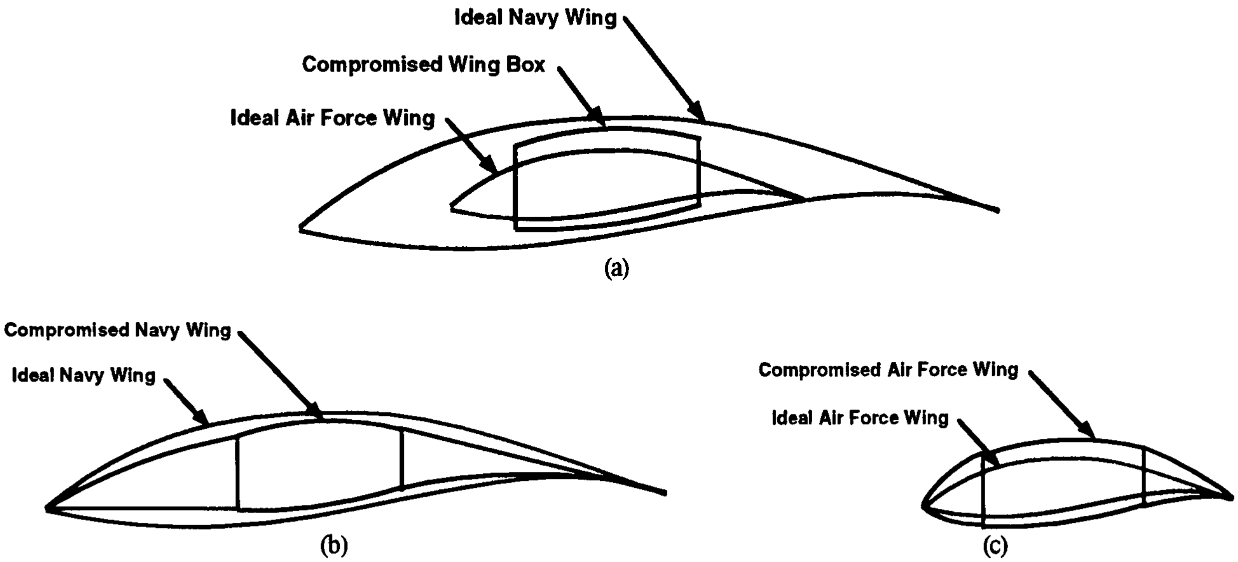


Figure 7-14. Compromised airfoils in (a) the common wing box design for (b) the Navy variant and (c) the Air Force variant.

The compromised design has significant assembly process flexibility but results in the following design issues:

- both large and small control surfaces have common attachments, and alignment of control surfaces to the airframe fuselage is critical
- with the folds, two piece control surfaces must be aligned relative to each other[15]
- both fixed tips and hinged folds must connect in some similar way and still carry their unique loads.

Some alignment issues are unique, some are common, and all are dictated by the approach that involves a common wing box.

7.2.3.4 The Complexity of the Selected Concept

Figure 7-15 combines the two issues discussed in Chapter 3 with the three issues discussed here to formulate functional and physical hierarchies for the aircraft. The functional hierarchy is broken into three sections, takeoff/landing requirements, normal flight requirements, and combat requirements. The physical hierarchy is broken into the airframe and propulsion branches. The airframe branch is further broken into the three unique variants, which share common fuselage modules that embody the keels, weapon bays, and the propulsion components as shown by the dashed line. The variants have unique control surfaces. The modules shown are for the baseline decomposition family.

The integral nature of the product is illustrated by the fact that few functions can be traced to single elements. In decomposition family 1, the weapon bays cross the boundary of modules 2 and 3, creating the need to align the four hinge lines across this boundary. The keels are each segmented in two places, creating six keel pieces and four alignment problems. The alignment of weapon bay hinge lines and the keel portions in modules 2 and 3 conflict with each other since all

[15] For simplicity, assume this and the previous alignment issue are required for proper aerodynamic function.

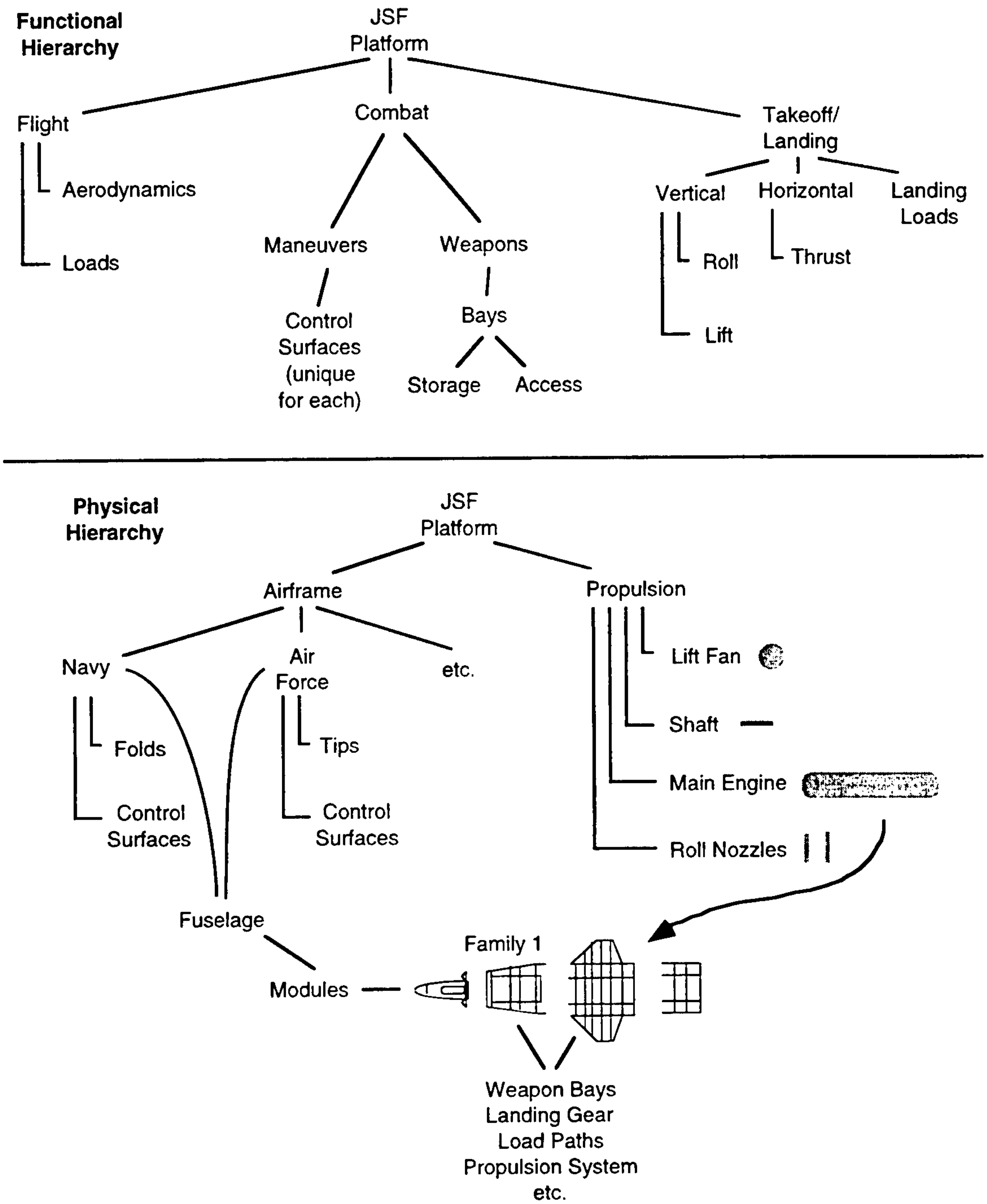


Figure 7-16. Functional and physical hierarchies of the selected concept.

6 alignments must be made in the butt line direction. The propulsion system is also segmented between modules 2 and 3, so shaft alignment can not be achieved in a single element and also conflicts with the keel and weapon bay hinge line alignments.

Section 7.3 analyzes this family and two others formally with the chain procedure and metrics to consider whether this integrality can be reduced, and to measure the integration risk.

7.3 Application of the Chain Metrics Method

This section describes how the CMM was applied to the JSF case study. I begin by explaining how the execution step in the CMM was applied to match the teaming arrangement and decomposition family approach. I then describe the aspects of the procedure that are common to all concept 1 decompositions: identification of KCs and SKCs, with several examples explained in detail. I then describe the execution step in detail for one decomposition of the JSF, with examples of how the chain capture procedure and all the metrics were applied. I continue with a summary discussion of decompositions from the other two families, and briefly compare the results for each. Last, I explain how the same analysis would be performed on decompositions of a second design concept.

7.3.1 CMM Applied to the JSF Case Study

7.3.1.1 Description of the CMM Execution Step as Applied to the JSF

Figure 7-17 summarizes how chains were captured and analyzed in this case study. There are six phases that comprise PKC identification, chain capture, and analysis with the metrics that match the decomposition steps - at the product level after the product was decomposed into systems, at the family level after the airframe was decomposed into a set of modules, and in each candidate decomposition within the modules. This set of phases was selected to correspond to the module team organization that matches the decomposition.

The first phase involves identification of the SKCs for the selected concept and is applicable to any decomposition of the concept. The second phase involves four steps that are applicable to all members of an airframe decomposition family: a decomposition family is selected, MKCs are identified, chains for each MKC are captured to identify AKCs in the airframe, and a KC Matrix is documented for the family. At this point each KC is categorized in one of the four categories

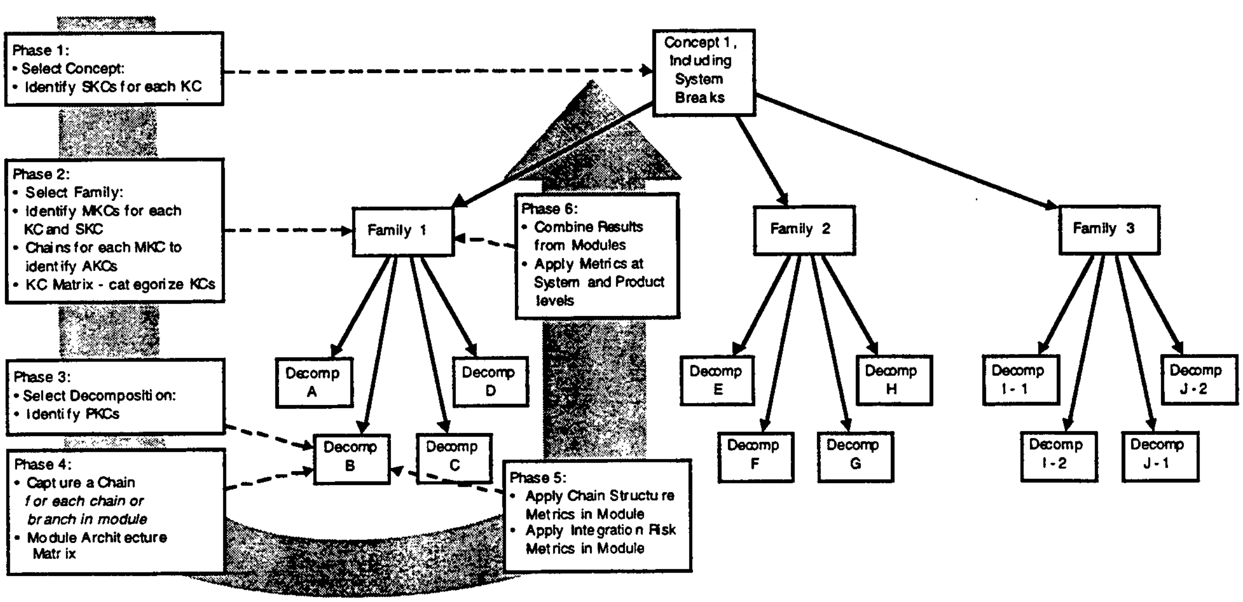


Figure 7-16. How the CMM execution step was applied to the hierarchy of decomposition families, using decomposition B of family 1 of concept 1 as an example.

described in Section 4.3.1.1. The third phase involves identification of PKCs and is conducted individually in each module and for each candidate decomposition. The fourth phase captures the chains documents the Module Architecture Matrix in each module and of the selected decomposition. The fifth phase applies the metrics to assess the chains in the modules, followed by an assessment at the system and product level as the sixth and final phase. Note that the chain capture procedure is applied in phases 2 and 4, and metrics are applied in the final two phases.

7.3.1.2 A KC Numbering System for the JSF Case Study[16]

Figure 7-18 describes a numbering system devised to track KCs in the context of SKCs, MKCs, and PKCs. The numbering system assisted not only in bookkeeping, but also serves to show the relative integrality of a KC just in the way the digits are populated. The first digit is the concept number followed by a decomposition letter. Note that the family is not denoted. The second digit is the KC number. The third digit is the SKC number. Two cases guide numbering the SKCs:

- The KC is delivered in only one system. In this case enter a zero since there is no SKC.
  Chain #x.#.0 (e.g. in concept 1, decomposition a, one system delivers KC #1 - Chain 1a.1.0)
- The KC spans systems. Here number the SKCs as the next digit starting with 1 (not zero).
  KC #x.#.# (e.g. SKC #1 - KC 1a.1.1)

The fourth digit is the MKC number. There are four cases that guide numbering the MKCs, which match the four categories of KCs described in Section 4.3.1.1:

- If the KC (when there is no SKC, i.e. #x.#.0) is delivered in one module of one system, enter a zero
  KC #x.#.0.0
- If there are SKCs, number the KC separately in each system. In one system, if the height is below the level of the system, i.e. if the portion of the chain in the system is completely within one module of that system, enter a zero.[17]
  KC #x.#.#.0

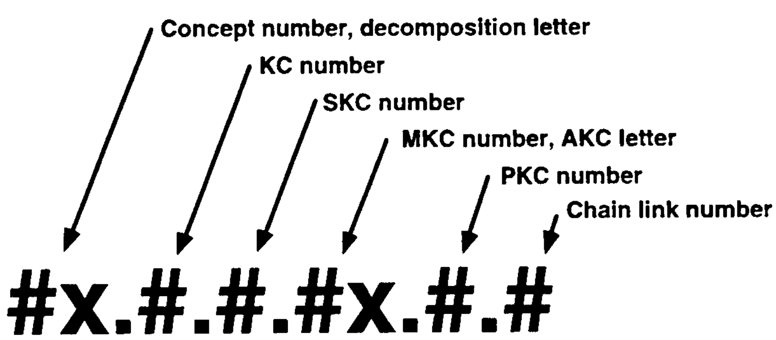


Figure 7-18. KC numbering system for JSF case study

[16] If the numbering system confuses the reader, proceed without exhaustive study as it will be illustrated in all the examples that follow.
[17] Note that the KC itself is delivered in more than one module if it is delivered in more than one system. But, in *any one system*, the SKC may be within one module.

- If the KC is delivered in one system, but spans modules in that system, there are one or more MKCs. Here number the MKCs as the fourth digit starting with 1.
  KC #x.#.0.#
- If there are SKCs, number the KC separately in each system. In one system, if the height is at the level of the system, i.e. if the portion of the chain in the system is in more than one module of that system, there are one or more MKCs. Here number the MKCs as the fourth digit starting with 1.
  KC #x.#.#.#

Each link in the chain for each MKC defines an AKC that is assigned to a module or the final assembly process. The AKCs in the modules will form branches of the chain. Number the links by preserving the MKC number and adding a letter. Number (one of) the root link(s) first with the letter 'a'.

KC #x.#.0.#x (KC delivered in more than one module of just one system), KC #x.#.#.#x (SKC delivered in more than one module)

Number each PKC by:

- For each KC, SKC, and AKC enter a zero.
  KC #x.#.#.#x.0
- For all PKCs created, number them by adding a fifth digit below a zero in the fourth
  KC #x.#.#.0.#

Finally, number each link of each chain in the 6th position of the number.

KC #x.#.#.#x.#.# (e.g. link 1 in a chain to deliver link 1a (an AKC) - Chain 1a.1.1.1a.0.1)

These numbers immediately reveal some level of the integrality of each KC. Recall that category 1 KCs, as defined in Section 4.3.1.1, are always integral, category 4 are always relatively modular, and categories 2 and 3 are the ones that the IPT has the most opportunity to control because they can be anywhere from modular to integral. The third and fourth digits in the KC number reveal the four KC categories:

- x.x - category 1 - multiple systems, multiple modules in one or more of *each* of the systems
- x.0 - category 2 - multiple systems, one module in *each* of the systems
- 0.x - category 3 - multiple modules of one system
- 0.0 - category 4 - one module of one system

In addition, the numbering system is similar to the way requirements tracking is accomplished in systems engineering tools, where a numerical hierarchy links related elements and denotes a parent-child relationship. In the KC numbering, branches of the chains in different modules or different systems that deliver the same KC will have identical first two digits. The system also allows the team to identify other elements that affect the same KCs by finding chain portions that share the same numbers. This provides both a data structure and a means to coordinate the activities in a dispersed IPT.

7.3.2 First Phase of the Analysis for Concept 1

The first phase of the analysis was applied to the concept studied in this case, and involved identifying SKCs. The systems - airframe, propulsion, doors that open in flight, and control surfaces - are the same for all decompositions of the concept, so this portion of the analysis was applicable to all airframe decompositions that were subsequently examined. The following begins by listing the KCs and explaining a few that will be illustrated throughout the remainder of the discussion, then describes how several are or are not further decomposed into SKCs.

7.3.2.1 Key Performance Parameters and Key Characteristics

As described in Section 7.1.1, 16 KCs were identified for concept 1 that are delivered in whole or in part by module 3 of decomposition family 1:

1. Major longitudinal load path alignment*
2. Major lateral load path alignment*
3. Main engine alignment*
4. Lift fan shaft alignment*
5. Roll nozzle relative alignments*
6. Weapon Bay door hinge line alignment*
7. Landing gear alignment relative to wells
8. Leading Edge drive alignment (of rotary drive)
9. Flaperon drive alignment (of actuator)
10. Tail Hook alignment to keels
11. Weapon Bay door edge gap and surface alignment*
12. Leading Edge inboard BL alignment to airframe body
13. Leading Edge outboard BL alignment to Wing Fold Leading Edge inboard edge (on versions with wings that fold)
14. Flaperon inboard BL alignment to airframe body
15. Flaperon outboard BL alignment to tip (flap inboard edge on versions with wings that fold that have an outboard control surface)
16. Interchangeable/Replaceable (I/R) Wing

The KCs marked with a '*' will be explored as examples in the remaining sections. KC #1 is the keel alignment issue discussed previously. KC #2 is a similar issue that runs from side to side in the wing. Figure 7-19 shows this alignment issue in one major structural element that carries the lateral loads. KCs 3-5 are the three alignment issues for the propulsion system that were discussed in Section 7.2.3.1. KC #6 is the weapon bay hinge line alignment issue, which also impacts KC #11.

The remaining KCs are used to explore the overall complexity of the design, but they are not described in detail.

7.3.2.2 SKCs

The KCs are decomposed into PKCs, specific dimensional attributes. The first step involves identifying SKCs: PKCs in multiple systems that deliver the KC. By convention, SKCs are only

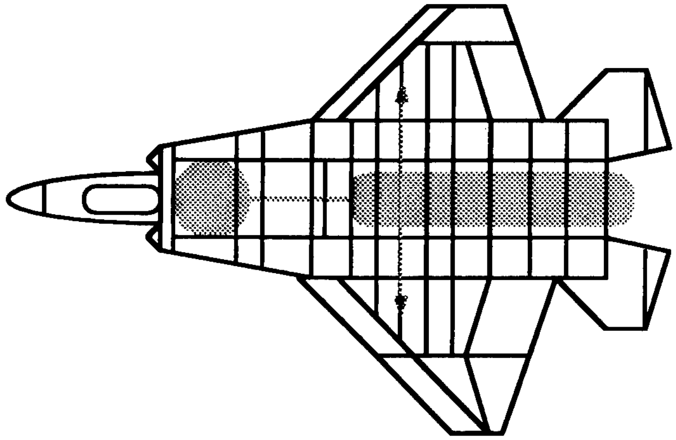


Figure 7-19. KC #2.

identified when the KC spans systems. Not every KC will have SKCs associated with it.

The following are four examples of the KCs in the above list, and the SKCs in the airframe that result:

- KC #6 - weapon bay door hinge line alignment - spans two systems, the airframe and in-flight operating doors system. The airframe aligns the ends of the hinges, and the hinges themselves are part of the door system. An SKC is denoted in each system as a result. Figure 7-20 shows the SKC in the airframe.
- KC #3 - main engine alignment - spans two systems, the airframe and main engine system. The airframe aligns the lug attach points of the engine, and the engine housing that attaches to the airframe aligns the principle axis of the main engine. An SKC is denoted in each system as a result. Figure 7-21 shows the SKC in the airframe.
- KC #1 - longitudinal load path (keel) alignment - is delivered in one system, the airframe. Therefore, no SKCs result. See Figure 7-22.
- KC #2 - lateral load path alignment - is delivered in one system, the airframe. Therefore, no SKCs result. See Figure 7-23.

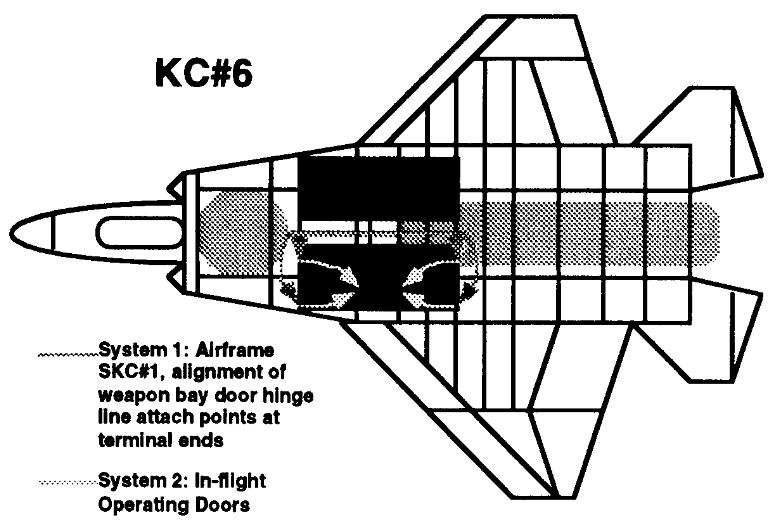


Figure 7-20. Airframe SKC for KC #6.

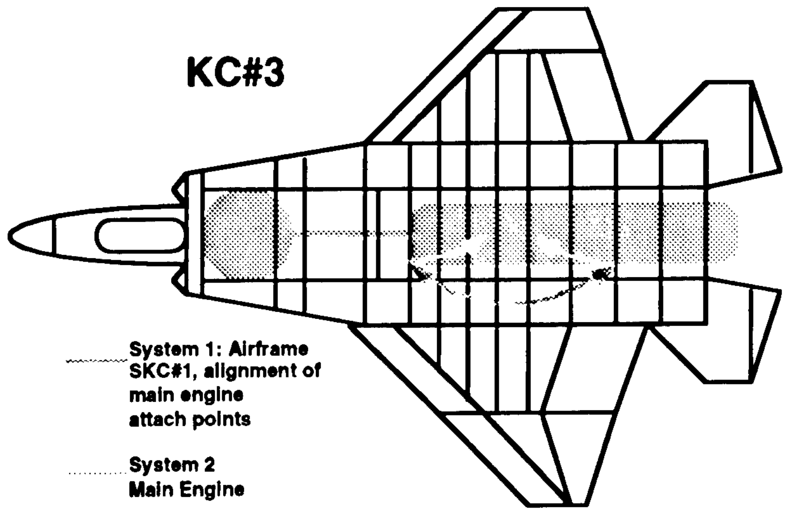


Figure 7-21. Airframe SKC for KC #3.

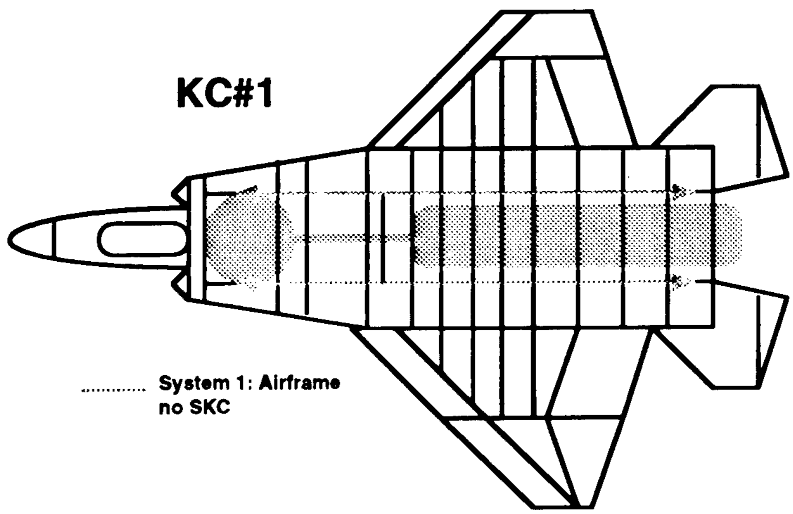


Figure 7-22. KC #1 has no SKCs because it is delivered in the airframe alone.

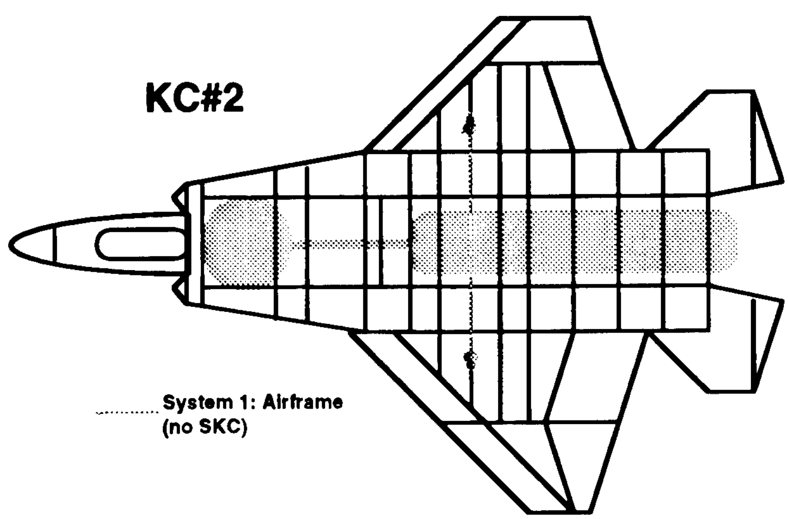


Figure 7-23. KC #2 has no SKCs because it is delivered in the airframe alone.

Table 7-3 lists the SKCs for each KC, and the systems responsible for each of the SKCs.

Table 7-3
SKCs for JSF Decomposition 1

KC #	KC description	SKC #	SKC system	SKC description
1	major longitudinal load alignment	1.0	airframe	
2	major lateral load path alignment	2.0	airframe	
3	main engine alignment	3.1	airframe	main engine attach point alignment at fwd and aft ends
		3.2	main engine	main engine lug alignments at fwd and aft ends relative to center line
4	lift fan shaft alignment	4.1	airframe	alignment of fwd main engine attach points to aft lift fan attach points
		4.2	main engine	position of shaft attach point relative to fwd lugs
		4.3	lift fan and shaft	position of aft shaft attach point relative to aft lift fan lugs
5	roll nozzle relative alignments	5.1	airframe	alignment of fwd main engine attach points to roll nozzle attach points
		5.2	main engine	position of roll nozzle attach points relative to fwd lugs
		5.3	lift fan and shaft	position of roll nozzle outlet relative to attach point to airframe
6	weapon bay door hinge line alignment	6.1	airframe	hinge attach points alignment at terminal ends
		6.2	closures: weapon bay doors	hinge alignment
7	main landing gear alignment relative to wells	7.1	airframe	position of main landing gear attach points to well boundary
		7.2	main landing gear	position of outer tire boundary to main landing gear attach point
8	leading edge drive alignment	0	airframe	
9	flaperon drive alignment	0	airframe	
10	tail hook alignment to keels	0	airframe	
11	weapon bay door alignment	11.1	airframe	hinge attach points alignment at terminal ends
		11.2	closures: weapon bay doors	edge position relative to attach points
12	leading edge inboard BL alignment to fuselage	12.1	airframe	position of leading edge drive to fuselage
		12.2	control surfaces: leading edges	position of inboard edge to drive attach point
13	Leading Edge outboard alignment (all) to Wing Fold Leading Edge inboard edge (on all with fold)	13.1	airframe	position of drive in wing to drive in fold
		13.2	control surfaces: leading edges	position of inboard edge of fold leading edge to drive attach point and outboard edge of wing leading edge to drive attach point
14	Flaperon/Flap edge inboard BL alignment to fuselage	14.1	airframe	position of flaperon/flap drive to fuselage
		14.2	control surfaces: leading edges	position of inboard edge to drive attach point
15	Flaperon/flap outboard BL alignment to tip (flaperon inboard edge on folds)	15.1	airframe	position of drive in wing to drive in fold
		15.2	control surfaces: flaperons/flaps	position of inboard edge of tip/flaperon to drive attach point and outboard edge of wing flaperon/flap to drive attach point
16	I/R wing	16.0	airframe	

7.3.3 Detailed Description of Remaining Phases for One Decomposition

The following describes the remaining phases of the execution step in detail as applied to decomposition B of family 1.

7.3.3.1 Decomposition Family 1 - Phase 2

The second phase of the method is applicable to all members of a decomposition family. The following describes how the method is applied to family 1. The focus of the study is on module 3, which houses all the lugs of the main engine, all portions of the wing, the structure to which the landing gear are attached, portions of the keels, and portions of the weapon bays.

7.3.3.1.1 Mate Options

There are two options for how module 3 will be connected to modules 2 and 4 that will be studied after generic chains, i.e. those with unassigned reference frames, are captured. The two options are:

1. feature-based, i.e. where the modules will directly mate at specific features.
2. by alignment, i.e. where the relative locations of the modules will be made by something else, such as a fixture.

The different mate options are accompanied by different assumptions that will alter the chains in different ways. Option 1 indicates that we have to assume "proximity" reference, i.e. the features will have to lie in certain regions of the modules in order to be used to mate the modules. That is, module 3 will have a reference frame in the forward potion that will mate to module 2. Module 3 will also have a different reference frame in the aft portion that will mate to module 4.

Option 2 indicates that the module reference frame will have to be in the lower portion of the module. This was immediately recognized by the team because a complete module will be covered by a skin on top when it arrives to mate with the other modules; the skin could be left off, but this is undesirable because it adds work later in the assembly process. The alignment mate option requires some stable set of features that can be accessed by the mate system. There will be no access to the top portion of module 3, so we know the approximate location of the reference frame: the lower portion of the modules.

7.3.3.1.2 Example MKCs

MKCs for the decomposition family are identified next. The following describes the MKCs for the same examples whose SKCs were shown above:

- KC 1.6.1 - the airframe SKC - alignment of weapon bay door hinge line attach points at terminal ends in airframe - lies in two modules, modules 2 and 3. The height in this case is the system level. Four MKCs result, which will be numbered 1.6.1.1, 1.6.1.2, 1.6.1.3, and 1.6.1.4. See Figure 7-24.
- KC 1.3.1 - the airframe SKC - alignment of main engine attach points in airframe- lies only in module 3. The height is below the system level. There are no MKCs, so the number will be 1.3.1.0. See Figure 7-25.
- KC 1.1.0 - the KC - longitudinal load path (keel) alignment - spans three modules. Four MKCs result, which will be numbered 1.1.0.1, 1.1.0.2, 1.1.0.3, and 1.1.0.4. See Figure 7-26.

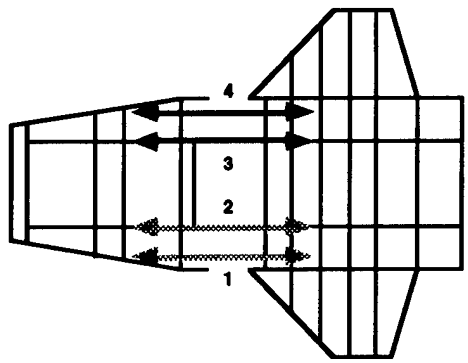


Figure 7-24. MKCs for KC #6 in decomposition family 1.

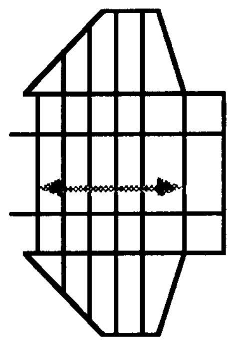


Figure 7-25. There are no MKCs for KC #3 in decomposition family 1.

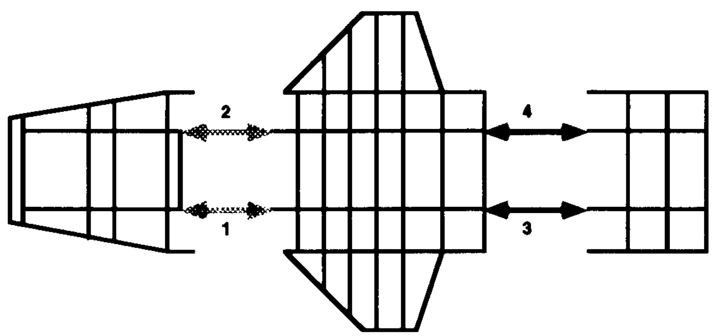


Figure 7-26. MKCs for KC #1 in decomposition family 1.

- KC 1.2.0 - the KC - lateral load path alignment - is delivered in module 3. There are no MKCs, so the number will be 1.2.0.0. See Figure 7-27.

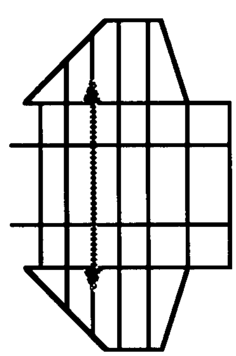


Figure 7-27. There are no MKCs for KC #2 in decomposition family 1.

7.3.3.1.3 Chains of MKCs

The next step is to capture a chain for each MKC. The chain at this level contains any root links and one link in each module. Each link in a module is an AKC in the module that will be expanded into a branch of the chain in the fourth phase of the method.

Figure 7-28 shows the chain for KC 1.1.0.1, alignment of the left keel portions in modules 2 and 3. Link 1a is the root link between the reference frames of modules 2 and 3. Link 1b is the AKC in module 2 from its reference frame to the end feature. Link 1c is the AKC in module 3 from its reference frame to the end feature. The remaining chains for the MKCs for KC #1, and for the MKCs of KC #6, are similar, three link chains.

7.3.3.1.4 KC Matrix

After the chains are captured for each MKC, each KC is categorized in the decomposition family, an early indication of the level of integrality that accompanies the decomposition. The four KC examples shown above correspond to the four categories as follows: KC #6 falls in category 1, KC #3 falls in category 2, KC #1 falls in category 3, and KC #2 falls in category 4. Table 7-4 lists the KCs by category for decomposition family 1.

The final step that is common to all members of the decomposition family involves documenting a KC matrix for the family, as described in Section 4.4.2.3.1. The KC Matrix utilizes the categorization discussed above. Figure 7-29 shows the full KC Matrix for family 1. Figure 7-30 shows just the airframe portion. The numbers correspond to the KC numbers listed above. Additionally, five dots are present in the matrix to represent KCs in the modules that were not actively studied in the case study, but that may change with the decomposition. Identifying these will prevent my underestimating integrality of other decompositions. The five dots correspond to the following for family 1:

- blue: KCs delivered only in module 1
- green: KCs delivered in modules 1 and 2
- yellow: KCs delivered in modules 1 and 3
- red: KCs delivered only in module 2
- black: KCs delivered only in module 4

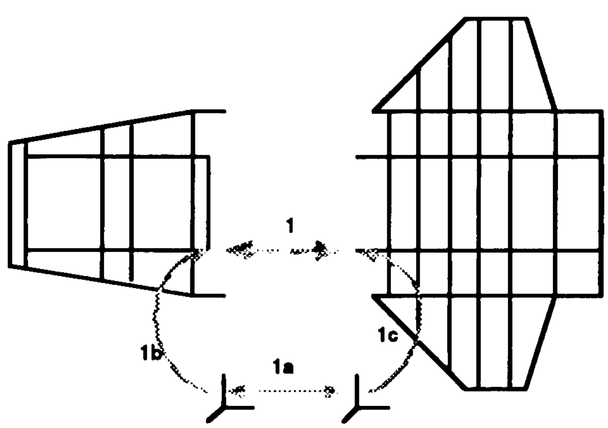


Figure 7-28. Chain for MKC #1 of KC #1 in decomposition family 1 - KC 1.1.0.1.

Table 7-4
KCs By Category in Decomposition Family 1

KC	Category
1	3
2	4
3	2
4	1
5	2
6	1
7	1
8	4
9	4
10	3
11	1
12	1
13	2
14	1
15	2
16	4

Module 1	●				Airframe										
Module 2	●	●	4,6,7,11, 12		6,11		12					4			
Module 3	○	1	2,8,9,(16)	14	6,11		12	14			4				7
Module 4			1,10	●				14							
WB Doors							In-flight Operating Doors								
LG Doors															
LE			13								Control Surfaces				
Flaperon/ Fold Flap			15												
Horizontal															
Vertical															
Main Engine			3,5										4		
Lift Fan													4		
Shaft										Lift Fan and STOVL Components					
Roll Ducts			5								5				
Main Landing Gear													Other Systems		

Figure 7-29. Full KC Matrix for decomposition family 1.

		A	B	C	D
Module 1	A	●			
Module 2	B	●	●	4,6,7,11, 12	
Module 3	C	○	1	2,8,9, (16)	14
Module 4	D			1,10	●

Figure 7-30. Airframe portion of KC Matrix for decomposition family 1.

Note that there are unlikely to be any KCs shared by modules 1 and 4, or by modules 2 and 4. In addition, it was the opinion of the LMTAS team that we had captured all potential KCs that would be shared by modules 3 and 4 as part of the study.

At this point we can first recognize KCs that are coupled. Recall how coupled sets of KCs across a set of modules are indicated in the KC Matrix as shown in Figure 4-28c. Across modules 2 and 3, there are six coupled KCs - 1 (Chains 1.1.0.1 and 1.1.0.2), 4, 6, 7, 11, and 12. Across modules 3 and 4, there are three coupled KCs - 1 (Chains 1.1.0.3 and 1.1.0.4), 10, and 14.

7.3.3.2 Decomposition B - Phases 3-5

The remaining phases of the method are applied to a specific candidate decomposition. The remainder of this detailed description is applied to decomposition B, shown in a WBS in Figure 7-30 and in a schematic in Figure 7-31. In this decomposition, module 3 broken into four main sub-assemblies: a right and left wing, an upper, and a lower, each of which is shown schematically in Figure 7-31. There are three other sub-assemblies: leading edge drives, and tips and folds.[18] The upper and lower sub-assemblies are each segmented into forward and aft components.

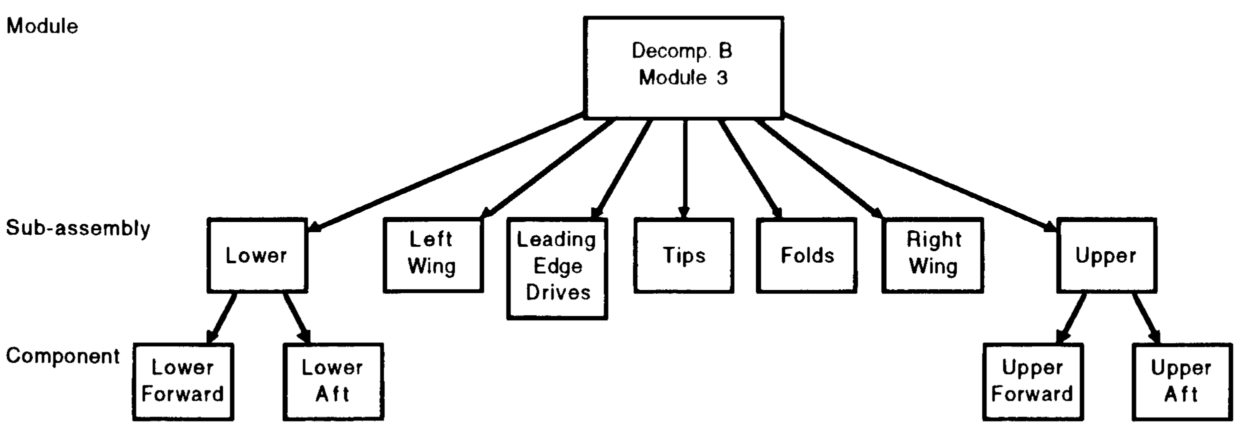


Figure 7-30. Decomposition B WBS.

[18] Recall any one aircraft will have only tips or folds.

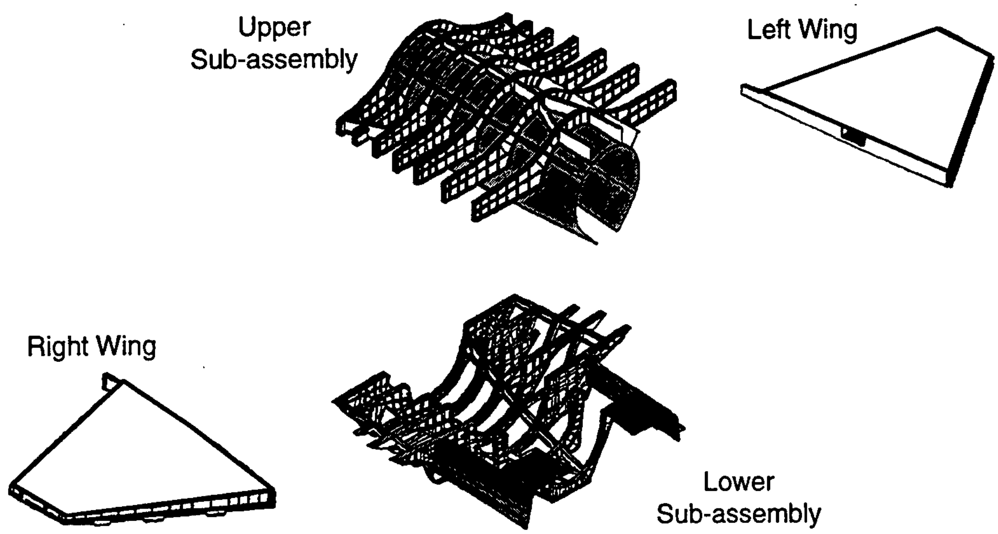


Figure 7-32. Schematic of decomposition B of module 3 in family 1.

7.3.3.2.1 PKCs

The third phase of the method involves identification of PKCs that are unique to the decomposition. An example of a PKC in decomposition B is found for KC #1. The keel portion found in module 3 will be in the lower sub-assembly. However, segmentation of the lower into forward and aft components further segments the two keels. Therefore there are two PKCs. Figure 7-33 shows a two dimensional schematic of the two lower components, and the two PKCs among the keel portions in the two components.

In addition, any KC that is delivered in one module of one system is translated into one or more PKCs, and an SKC that lies in one module may also spawn PKCs. KC #2 illustrates the case where a KC, delivered in one module, is translated into two PKCs. The main lateral load path is segmented in two places, spawning the two PKCs shown in Figure 7-34 depicted on a 2D schematic of the left wing, upper, and right wing sub-assemblies of decomposition B.

7.3.3.2.2 Chains

Phase four involves capturing all the chains in each module. The following are examples of chains in module 3 of decomposition B. For any SKC that lies completely in the module, and for all PKCs in the module, a chain is captured where all the links lie in the module. For MKCs, a branch of the chain is captured by expanding the AKC in the module. The chains are captured in three cases: generic, and then altered for the two mate options common to this family.

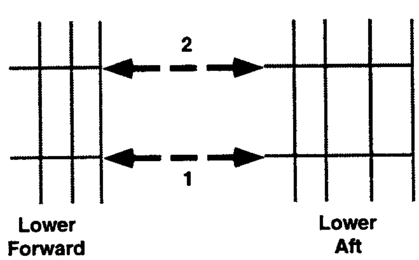


Figure 7-33. Two PKCs of KC #1 in decomposition B: KCs 1b.1.0.0.1 and 1b.1.0.0.2.

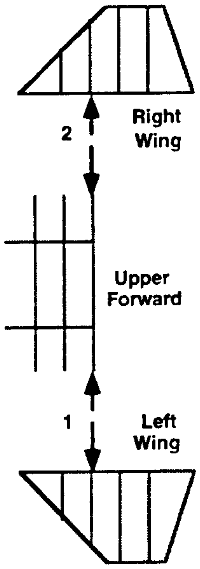


Figure 7-34. Two PKCs of KC #2 in decomposition B: KCs 1b.2.0.0.1 and 1b.2.0.0.2.

7.3.3.2.2.1 Generic

KC #3 is an example where the SKC is delivered in one module. Figure 7-35 shows the chain. One end feature each is in the upper forward and upper aft components. The root element is the upper sub-assembly. The root link occurs between the reference frames of the upper forward and upper aft components. One link is present in each component: the relationship between the component reference frame and the end feature.

KC #1 is an example where the AKCs in the module are each expanded into branches of the chain. Figure 7-36 shows the chain for AKC #1c (KC 1b.1.0.1c.0). The end feature is in the lower forward. Links in the branch include the relationship between the module 3 reference frame and the lower sub-assembly reference frame, the relationship between the lower sub-assembly reference frame and the lower forward component reference frame, the relationship between the lower forward component reference frame the end feature.

7.3.3.2.2.2 Mate Option 1

In mate option 1 - feature-based module mates - there are four reference frames that should be considered (and combinations for mating module 3 to modules 2 and 4):

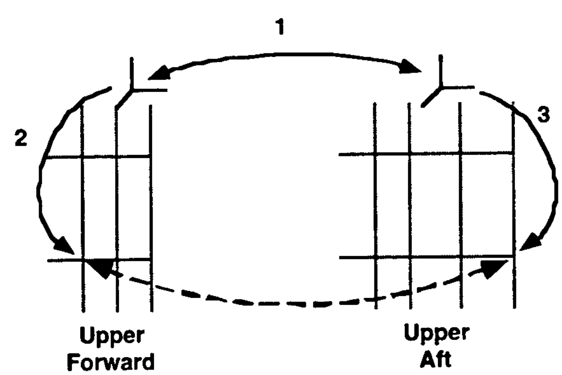


Figure 7-35. Chain for KC 1b.3.1.0.0.

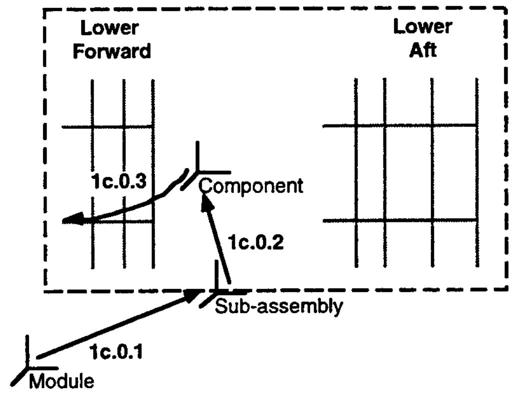


Figure 7-36. Chain for KC 1b.1.0.1c.0.

1. reference frame used in mating module 3 to module 2 is in the lower forward component
2. reference frame used in mating module 3 to module 2 is in the upper forward component
3. reference frame used in mating module 3 to module 4 is in the lower aft component
4. reference frame used in mating module 3 to module 4 is in the upper aft component

Here I focus on the choice of the first two, and will assume that module 3 will be mated to module 4 with features in the lower aft component. Because this choice will simplify a set of chains, and therefore alter the architecture and integration risk, it is important to make this choice systematically to understand the impact on the architecture. Figure 7-37 shows a blank module architecture matrix that will be used to illustrate the comparison. In the following, only the wing, upper, and lower sub-assemblies will be discussed and shown in the figures.

If the reference frame used in mating module 3 to module 2 is in the lower forward component, all chains for KCs with end features in the lower forward component will be simplified. Figure 7-38 shows an example. The chain is that for 1b.1.0.1c.0. The branch of the chain in module 3 now has only one link - from the module reference frame in the lower forward component to the end feature. Similar simplification will occur for KCs 1b.1.0.2c, 6, 7, and 11. In contrast, chains for KCs whose end features are not in the lower forward component will now pass through the

LF						
LA						
LW						
RW						
UF						
UA						

Figure 7-37. Blank Module Architecture Matrix for decomposition B.

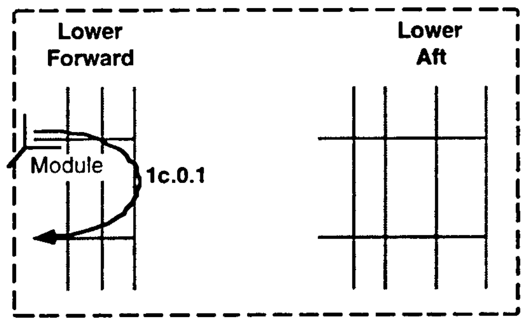


Figure 7-38. Chain for 1b.1.0.1c.0 when the reference frame used in mating module 3 to module 2 is in the lower forward component.

lower forward component. The module architecture matrix in Figure 7-39 shows how the KCs are delivered in this case. The highlighted block shows that KCs 4 and 12 are now delivered in a relationship involving the lower forward and upper forward components.

The opposite occurs if the reference frame used in mating module 3 to module 2 is in the upper forward component. Figure 7-40 the chain for KC 1b.1.0.1c.0 in this case, which is much more complex than in the case shown in Figure 7-38. The branch of the chain in module 3 now contains five links:

- 1c.0.1 - from the module reference frame to the upper forward component reference frame.
- 1c.0.2 - from the upper forward component reference frame to the upper sub-assembly reference frame
- 1c.0.3 - from the upper sub-assembly reference frame to the lower sub-assembly reference frame
- 1c.0.4 - from the lower sub-assembly reference frame to the lower forward component reference frame
- 1c.0.5 - from the lower forward component reference frame to the end feature

While the chains for KCs with their end features in the lower forward component are made more complex when the reference frame is in the upper forward, the delivery of KCs 4 and 12 are

LF	1,6,7,11				4,12	
LA	1	1,10				14
LW					12	
RW					12	
UF	2		2, 5, 9, 15, 16	2, 5, 9, 15, 16		
UA					3	

Figure 7-39. Module Architecture Matrix for mate option 1 where the reference frame used in mating module 3 to module 2 is assigned to the lower forward component, and reference frame used in mating module 3 to module 4 is in the lower aft component. The branch of the chains for KCs 4 and 12 in the module are relatively complex.

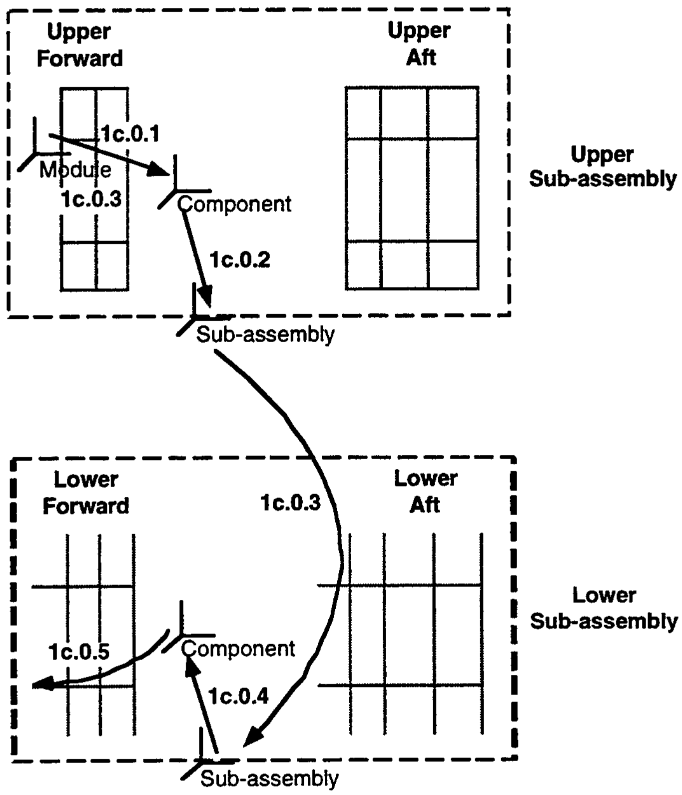


Figure 7-40. Chain for 1b.1.0.1c.0 when the reference frame used in mating module 3 to module 2 is in the upper forward component.

simplified because the module reference frame and end feature lie in the same component. The module architecture matrix in Figure 7-41 shows, as highlighted, that the delivery of KCs 1, 6, 7, and 11 are all made more complex while KCs 4 and 12 are now on the diagonal, representative of their simplified chain in the module.

7.3.3.2.2.3 Mate Option 2

Mate option 2 involves different choices. First, there is the choice of whether there will be a

LF					1,6,7,11	
LA	1	1, 10				14
LW					12	
RW					12	
UF	2		2, 5, 9, 15, 16	2, 5, 9, 15, 16	4, 12	
UA					3	

Figure 7-41. Module Architecture Matrix for mate option 1 where the reference frame used in mating module 3 to module 2 is assigned to the upper forward component, and reference frame used in mating module 3 to module 4 is in the lower aft component. KCs 1, 6, 7, and 11 are all delivered in more complex chains in this case.

single reference frame for mating module 3 with both modules 2 and 4. The alternative is to refixture module 3 after it is mated to one for mate to the other. The second choice is whether the module reference frame should be assigned to the lower forward or lower aft component.

For comparison with mate option 1, it is sufficient to illustrate the case where a single reference frame is chosen, and it is assigned to the lower forward component. When this assumption is made, all the chains involving the KCs shared between modules 3 and 4 now are affected by the lower forward component. Mate option 2 therefore further couples the KCs when a single reference frame is chosen. All 9 of these KCs are coupled. The Module Architecture Matrix in Figure 7-42 indicates this because two additional MKCs associated with KC #1 (the two for the keels between modules 3 and 4), KC #10, and KC #14 are now all affected by the lower forward component. The boxes highlighted indicate the three more complicated KCs when compared with the matrix in Figure 7-39.

7.3.3.2.3 Application of the Metrics in the Modules

The metrics are applied in the module in the fifth phase of the method. They can be applied to the generic chains, or to one or more of the options where reference frames are assigned. In this example they are applied to the module 3 chains for mate option 1, where the reference frame used in mating module 3 to module 2 is assigned to the lower forward component, and reference frame used in mating module 3 to module 4 is in the lower aft component.

7.3.3.2.3.1 Chain Structure Metrics

Table 7-5 shows the rating for each KC in module 3 of decomposition B, mate option 1, when the three chain structure metrics are applied. Begin with the Mapping Metric and take KC #3 as an example. The KC spans systems. The chain shown in Figure 7-35 shows that the height in the airframe system is the level of the upper sub-assembly, where the SKC in the airframe is delivered. The mapping rating is therefore yellow. KC #1 is another example. There are in fact six chains, and the rating will be assigned for the worst case. The two MKCs from module 3 to module 2 span modules but are delivered in one component, so they score green. The same is true for the two MKCs from module 3 to module 4. The two PKCs span components and are delivered at the height of components, so they too score green.

LF	1,6,7,11	1,10			4,12	14
LA	1					
LW					12	
RW					12	
UF	2		2, 5, 9, 15, 16	2, 5, 9, 15, 16		
UA					3	

Figure 7-42. Module Architecture Matrix for mate option 2 where a single reference frame used in mating module 3 to both modules 2 and 4 is assigned to the lower forward component.

Table 7-5
Chain Structure Metrics Ratings for Module 3 of Decomposition B, Mate Option 1

KC	mapping	coupling	crit path	integral
1	G	R	R	-
2	Y	G	Y	-
3	G	G	G	
4	R	R	R	-
5	R	G	G	-
6	R	R	R	-
7	R	R	R	-
8	Y	G	Y	-
9	Y	G	G	
10	G	R	Y	
11	R	R	R	-
12	R	R	R	-
13	R	G	Y	-
14	R	R	R	-
15	R	G	Y	-
16	Y	G	G	

The Coupling Metric is applied to the two groups of coupled KCs. In each case, both coupled sets involve a KC that scores red, so all coupled KCs are rated red in this metric.

The third metric, interaction with the critical path, can be applied by highlighting the parts, components, etc. that lie on the overall product critical path, or the critical path within the module. The ratings in Table 7-5 match the following critical path, shown in the Module Architecture Matrix in Figure 7-43[19]:

- Upper sub-assembly to Lower sub-assembly at module 3 assembly, so the boxes at the intersection of these sub-assemblies are shown in gray
- Lower sub-assembly, so the boxes at the intersection of these components are shown in gray
- Lower forward component, so this block on the diagonal is shown in gray

LF	1,6,7,11				4,12	
LA	1	1,10				14
LW					12	
RW					12	
UF	2		2, 5, 9, 15, 16	2, 5, 9, 15, 16		
UA					3	

Figure 7-43. IM with a critical path represented.

[19] This critical path is shown to illustrate the idea. The critical path would be an input from other analysis performed by the team. Section 4.4.2.3.3 describes how a critical path is transferred to an IM.

7.3.3.2.3.2 Integral Characteristics

Applying the criteria discussed in Section 4.3.1.5, all KCs are rated as integral except KCs 3, 9, 10, and 16, and should be assessed for the level of integration risk using the risk metrics.

7.3.3.2.3.3 Populating Chains for Application of the Risk Metrics

Before applying the integration risk metrics, assumptions had to be made regarding the supply chain and technologies to be used. Two supply chain assumptions were considered: each module will be designed and made by a different company in a teaming arrangement, and LMTAS would outsource all but one sub-assembly and one component in that one sub-assembly. We could not determine which elements would be retained in-house, so the following assumes all sub-assemblies and components are outsourced to show a higher level of integration risk than would be encountered. The selection of elements to be retained can then be made according to which mitigate integration risk the most by reducing the organizational boundaries and level of dependency, as discussed in Section 4.3.2.1.

Two scenarios were investigated involving process technology: 1) an aggressive process technology in the lower sub-assembly of decomposition B, entailing a higher level of integration risk for chains in that sub-assembly; and 2) an aggressive process technology in the wings. Each option is shown in the comparison that follows.

7.3.3.2.3.4 Risk Metrics

Each integration risk metric is applied to the integral KCs. Table 7-6 shows the results for decomposition B for each technology scenario considered. The way to read this table is the following. The first two columns - the complexity and organizational boundary metrics - apply to both cases. The third and fourth columns show the rating on the process capability metric in case 1, and the combination of the three metrics in this case rated high, medium, or low risk based

Table 7-6

Integration Risk Rating of Integral KCs for Two Process Scenarios - Decomposition B

KC	complex.	org.	tech. - 1	risk - 1	tech. - 2	risk - 2
1	G	Y	Y	MED	G	
2	Y	Y	Y	HI	Y	HI
3						
4	Y	R	Y	HI	G	HI
5	Y	Y	G	MED	Y	HI
6	G	G	Y		G	
7	G	G	Y		G	
8	G	G	G		Y	
9						
10						
11	G	G	Y		G	
12	R	Y	Y	HI	Y	HI
13	G	Y	G		Y	MED
14	Y	Y	Y	HI	Y	HI
15	Y	Y	G	MED	Y	HI
16						

on the criteria in Section 4.3.2.3. The fifth and sixth columns show the rating on the process capability metric in case 2, and the combination of the three metrics in this case.

Take KC #1 as an example. MKC and PKC chains involve one sub-assembly out of a possible four in this module, so the complexity metric is rated green. The PKC chains cross components in the lower where an organization boundary among lowest tier suppliers is possible, but these suppliers will be members of the same sub-assembly in the WBS. This is a yellow organizational boundary. The MKC chains are in a single component. In the case where the process technology in the lower sub-assembly is aggressive, KC #1 is rated as medium risk based on process capability. In the case where the technology in the wing is aggressive, KC #1 is rated as low risk based on process capability.

7.3.3.2.4 Combined Results from Each Module

The final phase of the analysis involves combining the results from several modules and several systems, and again applying the metrics to further investigate the level of integration risk. In the case of decomposition B, this step can not be illustrated because only one module of one system was investigate. It would have involved combining the results from module 3 with similar analysis in the other modules to attain an overall architecture rating for the airframe decomposition, and with the same analysis in other systems. This phase is illustrated briefly in the description of family 3, where more than one module was investigated.

7.3.3.2.5 Architecture and Integration Risk of Decomposition B

The architecture is documented in the final step of the CMM. The list in Section 4.6 comprises what should be documented in order for the architecture of a concept and decomposition to be compared. Each of the following were discussed above, and would be documented as the architecture for decomposition B:

- a summary of the architecture: category of each KC and a KC Matrix
- a list of the integral KCs and coupled KCs[20]
- risk assessment of each integral KC
- the chain for each integral KC, with the supplier, process, and capability information noted (as it becomes available)
- Module Architecture Matrices for each module containing a high risk integral KC.

Two additional portions of the architecture documentation are discussed further in Section 7.4:

- results of quantitative analysis
- mitigation plans.

7.3.3.3 Summary of Decompositions C and D

There are two additional decompositions in family 1. The following summarizes the results of similar analysis of each. Section 7.3.4 summarizes an analysis of the decompositions in the other two families, followed by a comparison of all decompositions in Section 7.3.5.

[20] In this case the coupling indicated is among modules. The prescription could also show coupling among sub-assemblies in module 3.

Decomposition C involves different wing configurations than those of decomposition B. This configuration improves some aspects of the design, but one significant penalty is that KC #16 - interchangeable /replaceable wings - can not be satisfied. While the decomposition was studied for some time by LMTAS as a different decomposition because it would have different scoring on other analyses, e.g. performance, critical path time, etc., my analysis with the CMM showed it has an identical architecture as decomposition B, except for KC #16. The WBS is the same for decomposition B. The difference is in the details of how the elements are attached, but, because the module mate options are the same, the functional-physical mapping and integration risk are in the main unchanged.

Decomposition D is substantively different in terms of its architecture. In module 3 there are three major sub-assemblies instead of four, with portions of what was the upper sub-assembly now split into the two wings. Effectively, decomposition D splits the upper into left and right components called "inners" instead of forward and aft, and these left and right inner components are attached to the wings first instead of each other in a separate sub-assembly. Figure 7-44 shows the WBS.

Table 7-7 shows the rating of the three chain structure metrics for decomposition D with the same mate option applied as in decomposition B.

7.3.4 Summary of Decompositions in Families 2 and 3

The following summarizes the analysis of six additional decompositions in two families.

7.3.4.1 Decomposition Family 2

Figure 7-45 shows the four modules of decomposition family 2: the "forward", "mid", "upper", and "lower." The portions of module 3 in family 1 are in this family split among the upper and lower modules, as highlighted in the figure. The study therefore expanded to two modules, the upper and lower, in this family to compare the change in architecture and integration risk relative to family 1. Two decompositions of the upper called E and G were investigated in detail. The same decomposition of the lower applies to both.

7.3.4.1.1 Mate Options

This decomposition was conceived to facilitate a feature-based mate between modules. The

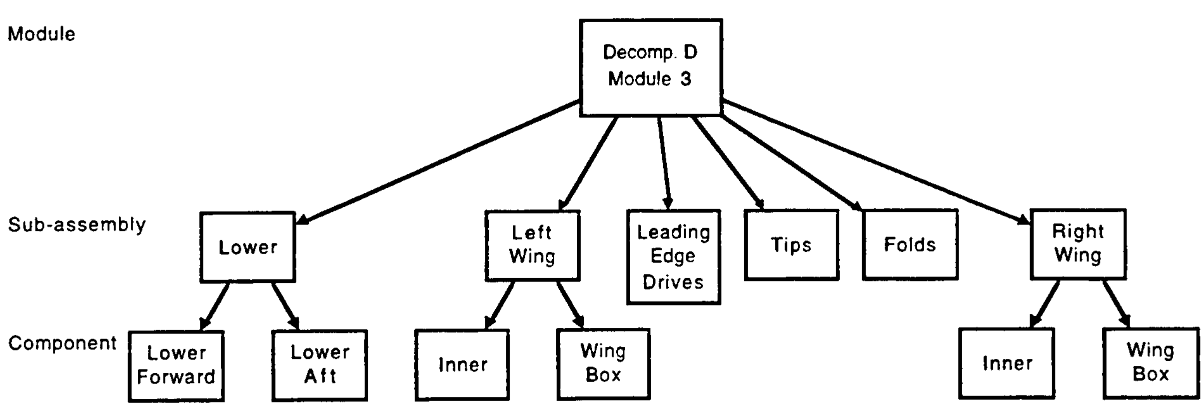


Figure 7-44. Decomposition D.

Table 7-7
Chain Structure Metrics Ratings for Module 3 of Decomposition D, Mate Option 1

KC	hierarchy	coupling	crit path	integral
1	G	R	Y	
2	Y		Y	-
3	G		G	
4	R	R	R	-
5	R		Y	-
6	R	R	Y	-
7	R	R	Y	-
8	Y		Y	-
9	G		Y	
10	G	R	Y	
11	R	R	Y	-
12	R	R	R	-
13	R		Y	-
14	R	R	R	-
15	R		Y	-
16	Y		Y	-

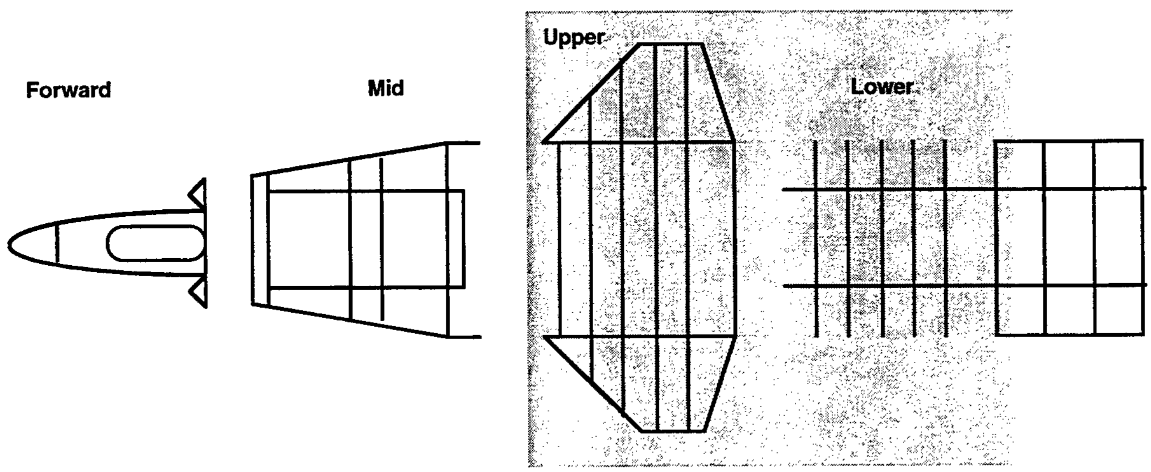


Figure 7-45. Decomposition Family 2. The shaded region shows the portion of the modules that contain the same elements as module 3 in family 1.

upper, which sits on top of the forward portion of the lower, will be mated via matching features to the lower. The mid could then be mated to the lower or upper. The following shows the results for the mid mated to the lower. Both options were considered in the full case study.

7.3.4.1.2 Categories, KC Matrix, and Coupling

Figure 7-46 shows the MKCs and their chains for KC #1 in family 2. In this family, each keel is segmented into only two pieces as opposed to three as in family 1, so there are only two MKCs. The chains for these MKCs are simple three link chains like those for the MKCs in family 1 shown in Figure 7-27.

Figure 7-47 shows the full KC Matrix for family 2, which shows the category of each KC. Figure 7-48 shows just the airframe portion. There are three changes from family 1: KC #2

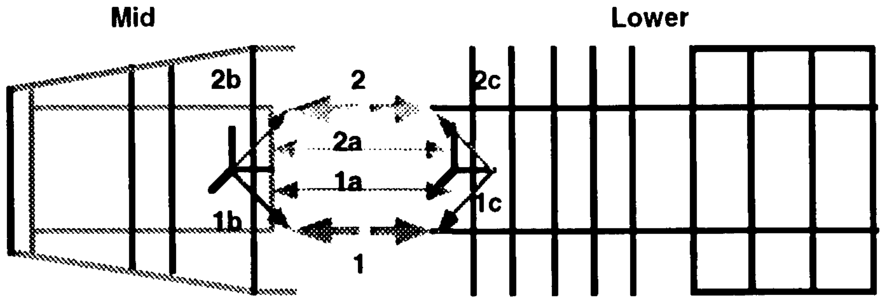


Figure 7-46. MKCs and their chains for KC #1 in family 2.

Fwd	●				Airframe										
Mid	●	●		4,6,7,11, 12	6,11		12					4			
Upper	C	16	8,9	4,12,14			12	14			4				
Lower	C	1,16	2,16	10,●	6,11			14							7
WB Doors							In-flight Operating Doors								
LG Doors															
LE			13								Control Surfaces				
Flaperon/ Fold Flap			15												
Horizontal															
Vertical															
Main Engine			3,5										4		
Lift Fan													4		
Shaft										Lift Fan and STOVL Components					
Roll Ducts			5								5				
Main Landing Gear													Other Systems		

Figure 7-47. Full KC Matrix for decomposition family 2.

		A	B	C	D
Fwd	A	●			
Mid	B	●	●		4,6,7,11, 12
Upper	C	C	16	8,9	4,12,14
Lower	D	C	1,16	2,16	10,●

Figure 7-48. Airframe portion of KC Matrix for decomposition family 2.

changed from category 4 to 3, KC #10 changed from category 3 to 4, and the unmodeled KCs represented by the yellow dot are now potentially split among the upper and lower. There are now different interactions among the modules, as compared by the content of Figures 7-29 and 7-47.

Figure 7-49a shows the WBS for decomposition E, and Figure 7-49b shows the WBS for decomposition G. The difference between the two decompositions involves the structure sub-assembly of the upper module. Decomposition E splits the structure sub-assembly into left, center, and right components like in the wings and upper sub-assemblies of the decomposition B. Decomposition G has two components that cross all these regions of the upper.

7.3.4.1.3 Result from the Remainder of the Analysis: Architecture and Integration Risk

The remaining steps in the method, the chain capture procedure and metrics, are applied to decompositions E and G to generate the architecture. The results shown below in Section 7.3.5 indicate that these two decompositions do not significantly alter the architecture because the level of integrality is similar. The level of integration risk is in fact higher than the risk found in the decompositions of family 1. The differences would be captured in an architecture description that includes:

- the category of each KC and KC Matrix, shown above
- the integral KCs and coupled KCs, which are captured in the KC Matrix

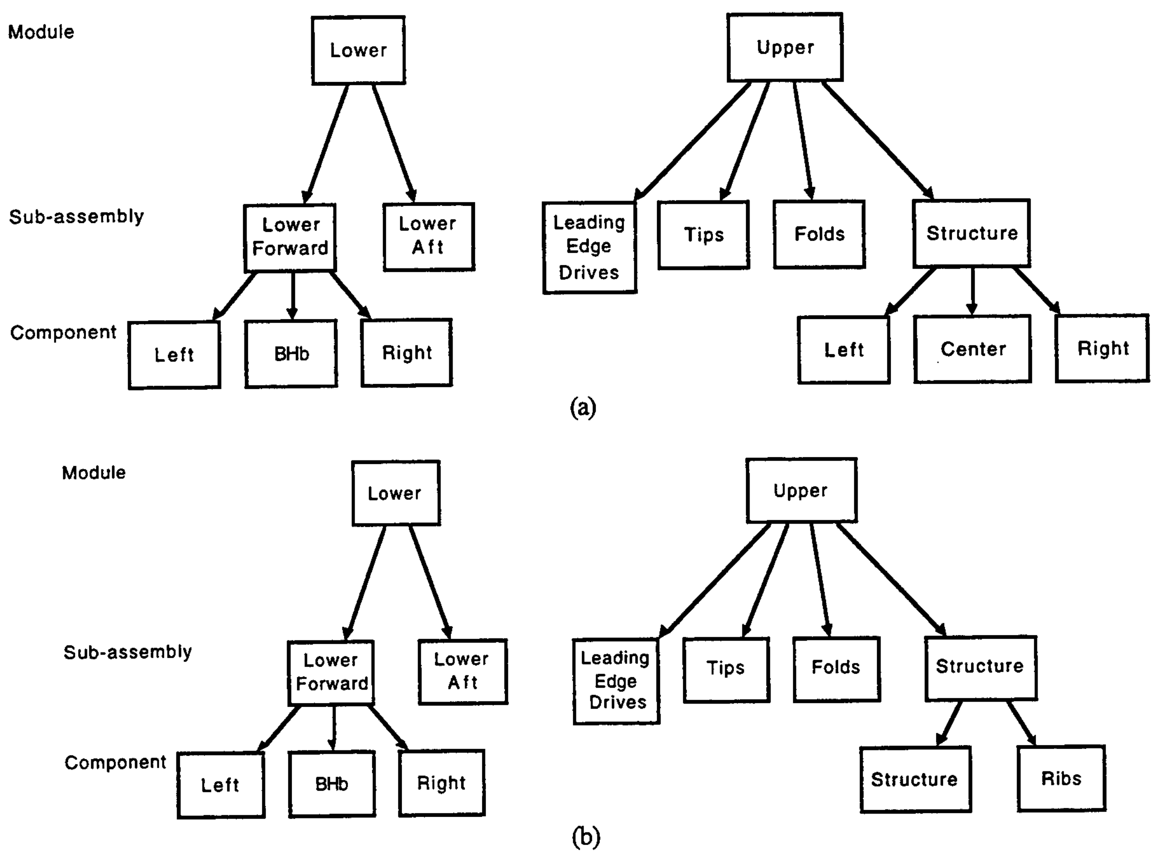


Figure 7-49. WBS for (a) decomposition E and (b) decomposition G.

- risk assessment of each integral KC
- the chains for the integral KCs
- the Module Architecture Matrices for the upper and lower modules which were generated as part of the study.

7.3.4.2 Decomposition Family 3

Following analysis of the first two families, the LMTAS team and I began to consider radically different decompositions in order to see if the architecture and integration risk of the concept could be changed significantly. Decomposition family 3 is an example of decompositions considered, and is in this way indicative of what the CMM portrays as iteration that considers alternate decompositions. Figure 7-50 shows the modules in this decomposition: the "forward", "bay", "upper", and "aft." Because portions of module 3 are now dispersed to three modules, as indicated in the figure, the scope of my analysis expanded to three modules.

In studying this family, two decompositions of the bay module called I and J were considered. These were combined with the two decompositions of the upper from family 2 - E and G - to create four candidate decompositions in family 3. No decomposition of the aft was considered because there was little influence on the analysis to be gained. The four decompositions are called the following:

- I-1: I with upper of E
- I-2: I with upper of G
- J-1: J with upper of E
- J-2: J with upper of G

7.3.4.2.1 Mate Options

A feature-based mate option was preferred for this set of modules. Again a main choice involved how modules would be mated, i.e. whether the bay will mate to the upper or aft. Both options were considered in the case study, while the summary presented here assumes the bay is mated to the upper. There is a second choice that is discussed below: when the bay mates to the upper,

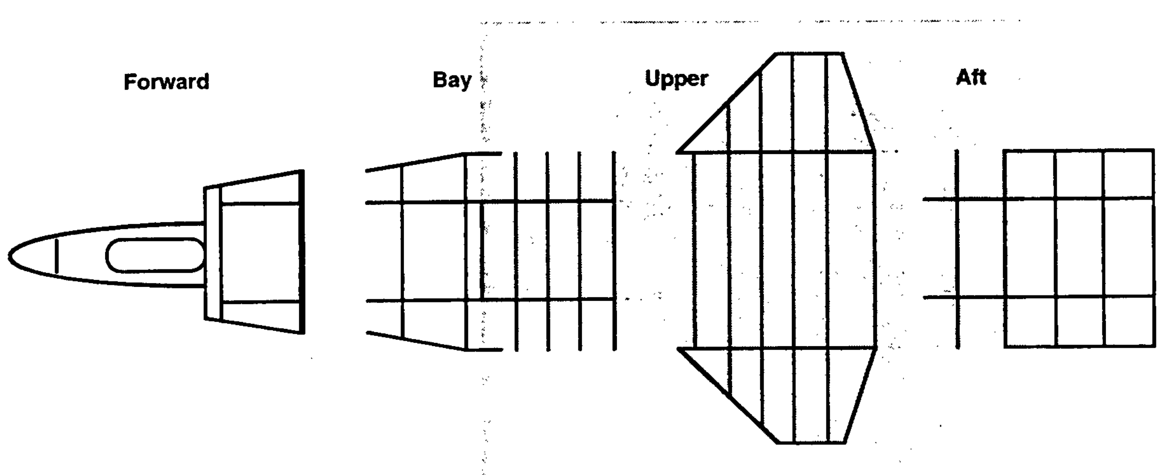


Figure 7-50. Decomposition Family 3. The shaded region shows the portion of the modules that contain the same elements as module 3 in family 1.

to what portion of the bay module should the reference frame be assigned? This is a proximity/assignment decision that was explored in detail in the case study. As with family 2, the impact that both choices have on the architecture assists in understanding which decision is best and lends insight into the "height" aspect of the mapping metric as discussed in Section 4.3.1.1.

7.3.4.2.2 Categories, KC Matrix, and Coupling

Figure 7-51 shows the MKCs and their chains for KC #1 in family 3. In this family, each keel is segmented into three pieces similar to those in family 1, so there are four MKCs. The chains for MKCs 1 and 2 are simple three link chains like those for similar MKCs in families 1 and 2 shown in Figure 7-28 and 7-46. However, the chains for MKCs 3 and 4 are more complex. The keel alignment KC is now affected by the upper module, which does not contain a portion of the keel but is the root element because it is the element to which the root sub-elements - the bay and aft modules - are mated at the point where the MKC is delivered. This is the type of insight into KC delivery that is only attained when the chain capture procedure is followed. If the bay-aft mate were made, the chains for MKCs 3 and 4 of KC 1 would be simplified, but the chains for KCs 14 and 16 would become more complex.

Family 3 is also different in terms of KC #6. The bay module contains the entire weapon bay, so KCs 6 and 11 are now category 2 instead of category 1. There are no longer any MKCs for KC #6 in the airframe.

Figure 7-52 shows the full KC Matrix for family 3, which shows the category of each KC. Figure 7-53 shows just the airframe portion. Six KCs change category in this decomposition. KCs 6, 7, 10, and 11 are reduced one category, and KCs 2 and 16 are raised one category. There

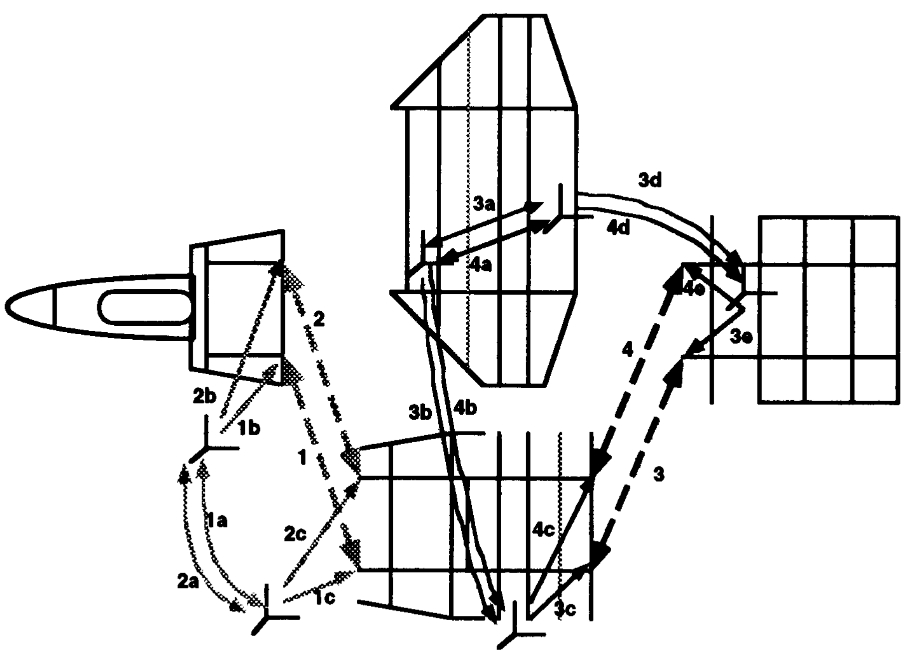


Figure 7-51. MKCs and their chains for KC #1 in family 3. The chains for MKCs 3 and 4 are more complex than those in either of the other families.

Fwd	●●●	4,			Airframe										
Bay	1,●○	●	4,12				12								
Upper	○	1,2,16	8,9	14			12	14			4				
Aft	○	1	1,16	10,●				14							
WB Doors		6,11					In-flight Operating Doors								
LG Doors															
LE			13								Control Surfaces				
Flaperon/ Fold Flap			15												
Horizontal															
Vertical															
Main Engine			3,5										4		
Lift Fan													4		
Shaft										Lift Fan and STOVL Components					
Roll Ducts			5								5				
Main Landing Gear		7											Other Systems		

Figure 7-52. Full KC Matrix for decomposition family 3.

		A	B	C	D
Fwd	A	●●●	4,		
Bay	B	1,●○	●	4,12	
Upper	C	○	1,2,16	8,9	14
Aft	D	○	1	1,16	10,●

Figure 7-53. Airframe portion of KC Matrix for decomposition family 3.

are again different interactions among the modules. In addition, there are three changes in the unmodeled KCs represented by the colored dots. The green dot is now contained in one module, some of the red dot KCs are now contained in the forward and bay modules as opposed to just in a single module in the previous two families, and the yellow dot KCs now potentially are shared among the forward and one or more of any of the other modules. The unmodeled KCs illustrate how each decomposition can significantly change the way KCs are dispersed among the physical elements in a decomposition.

7.3.4.2.3 Decompositions I-1 and I-2: Bay Module KCs

Figure 7-54 shows decomposition I, both a WBS and schematic. Decomposition I is aggressive.

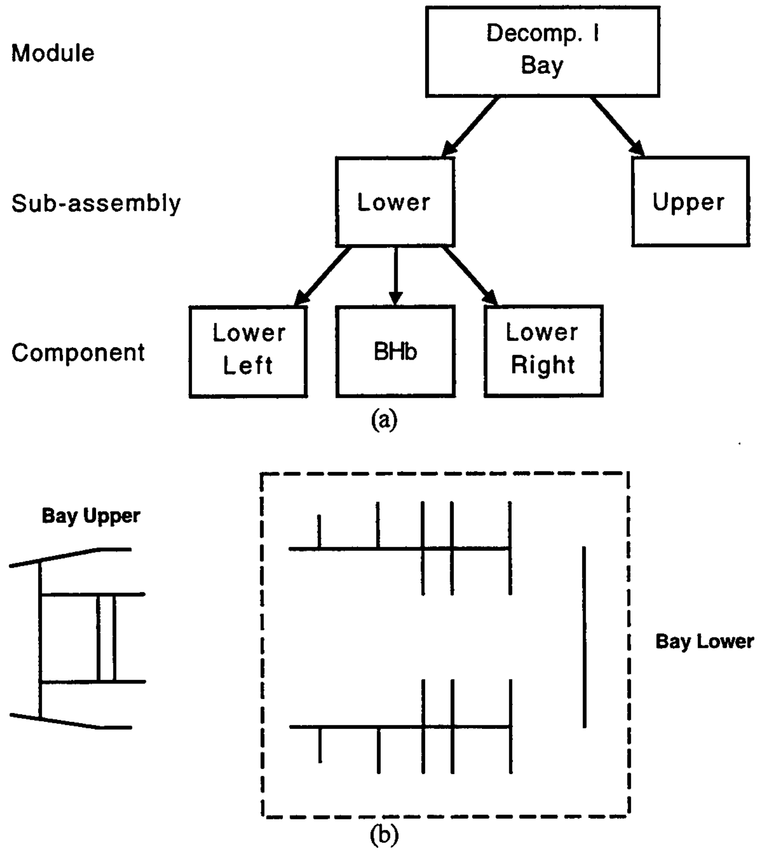


Figure 7-54. Decomposition I (a) WBS and (b) schematic.

There are station, water, and butt line breaks to attempt to modularize delivery of the KCs. There are two sub-assemblies, the bay upper and bay lower. The bay lower sub-assembly is broken into three components: a left and right that each contain a landing gear well, a full weapon bay (except the terminal end at the main bulkhead 'BHb'), and a whole keel section in this module; and BHb is a separate component assumed to be an integrally machined piece.

KCs 1 and 4 illustrate the reference frame proximity and assignment trade-off for this module. The bay module reference frame can be assigned to either the upper or lower sub-assembly. Figure 7-55 shows the two proximity choices; options 1 and 2. The proximity of each option leads to a reference frame assignment, to the bay forward for option 1 and to BHb in option 2.

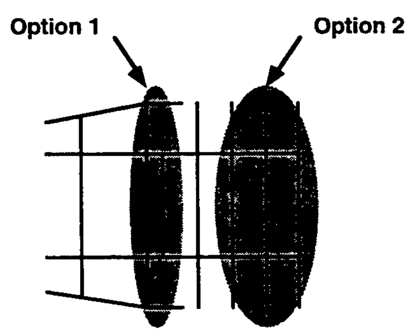


Figure 7-55. Two proximity options for the bay module reference frame used to attach the bay to the upper.

Figure 7-56 shows the branches of the chains in the bay module for KCs 1i.1.0.1 and 1i.4.1.1a (which is a root link) for option 1. The chain for KC #1 is more complex than that for KC #4. Figure 7-57 shows the chains for the same MKCs for option 2. The chain for KC #4 is more complex than that for KC #1. Clearly there is a trade-off as to which KC will be delivered in a more complex fashion. In fact, there are several listed in Table 7-8 that are made more simple or more complex in each option. The choice can be made on a basis of total numbers of KCs simplified or complicated in each case, or later after the integration risk is studied in each case. The remainder of this example shows the results assuming option 1.

Table 7-9 shows the chain structure metrics ratings for decomposition I-1 and I-2 for the KCs in the bay module in when mate option 1 is applied.

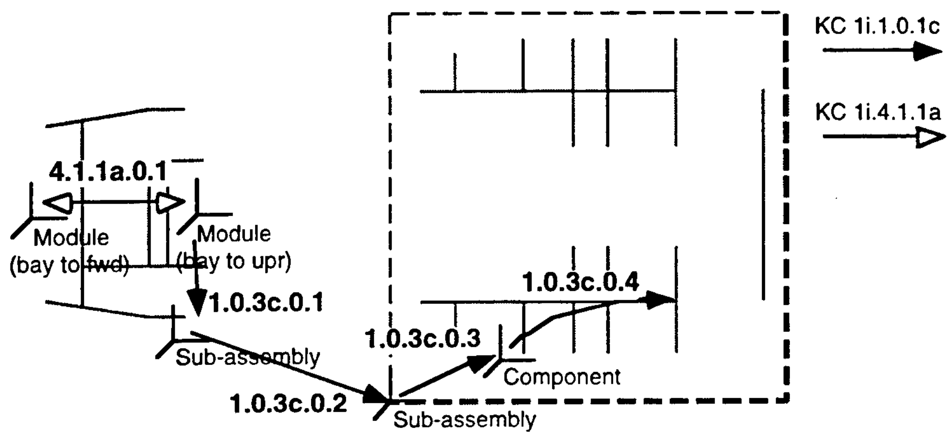


Figure 7-56. Chain branches in the bay module for reference frame proximity option 1 - KCs 1i.1.0.3c and 1i.4.1.1a

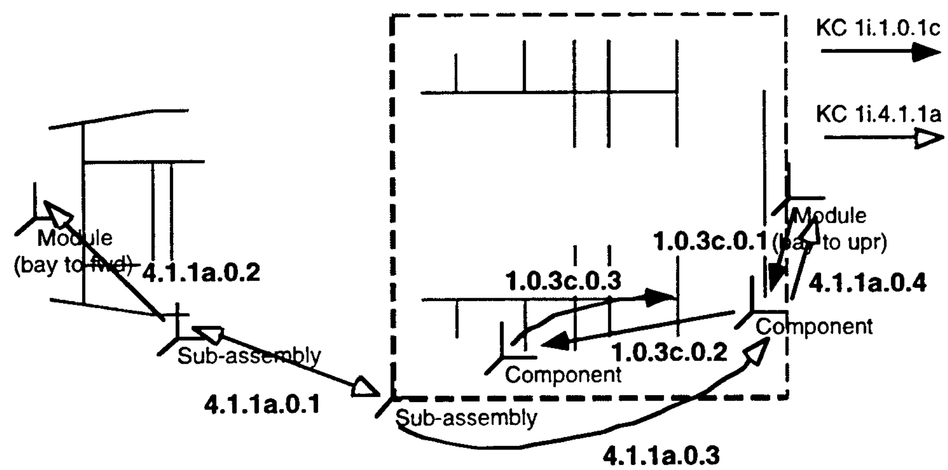


Figure 7-57. Chain branches in the bay module for reference frame proximity option 2 - KCs 1i.1.0.3c and 1i.4.1.1a

Table 7-8

Relative Complexity of KC Delivery Depending on Reference Frame Proximity - Decomposition I

	Option 1	Option 2
Simplified	**4, 12, 16.0.1**	**1, 2, 16.0.2**
Complicated	**1, 2, 16.0.2**	**4, 12, 16.0.1**

Table 7-9
Chain Structure Metrics Rating for Decomposition I

KC	mapping	coupling	crit path	integral
1	R	R	Y	-
2	R	R	Y	-
4	R	R	R	-
6	Y	G	G	
7	Y	G	G	
11	Y	G	G	
12	R	R	R	-
16	R	R	R	-
red dot	Y	R	R	-

7.3.4.2.4 Decompositions J-1 and J-2: Bay Module KCs

Decomposition J is more conventional with a station line split at the aft-most point of the mid in family 2 and module 2 in family 1, as shown in Figure 7-58.

Table 7-10 shows the chain structure metrics ratings for decompositions J-1 and J-2 for the KCs in the bay module. Note that the coupled sets of KCs are the same in all family 3 decompositions.

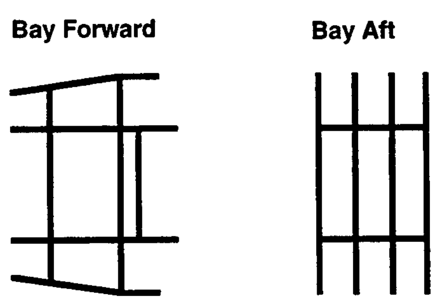


Figure 7-58. Decomposition J schematic.

Table 7-10
Chain Structure Metrics Rating for Decomposition J

KC	mapping	coupling	crit path	integral
1	R	R	R	-
2	R	R	Y	-
4	R	R	R	-
6	R	G	Y	-
7	R	G	Y	-
11	R	G	Y	-
12	R	R	R	-
16	R	R	R	-
red dot	Y	Y	R	-

7.3.4.2.5 Combined Results in Multiple Modules

The sixth phase of the method as applied in this case study involved combining results in multiple modules to create a combined architecture assessment. This phase can be illustrated in the results of family 3. While the description above was focused on the bay module, the same was conducted in the upper module for decompositions E and G. Then, four combinations of these lead to the four decompositions of family 3.

Tables 7-11 and 7-12 show the chain structure metric ratings for the upper module in the context of the mate option assumptions in family 3. Note that KCs 1, 2, 4, 12, and 16 are rated as

Table 7-11

Chain Structure Metrics Rating for the Upper from Decomposition E in the Context of Family 3

KC	mapping	coupling	crit path	integral
1	Y	R	G	-
2	Y	R	G	-
3	G		G	
4	Y	R	G	-
5	Y		G	
8	G		G	
9	G		G	
12	R	R	G	-
13	R		G	-
14	R	Y	G	-
15	R		G	-
16	R	R	G	-

Table 7-12

Chain Structure Metrics Rating for the Upper from Decomposition G in the Context of Family 3

KC	mapping	coupling	crit path	integral
1	R	R	G	-
2	R	R	G	-
3	Y		G	
4	R	R	G	-
5	R		G	-
8	Y		G	
9	Y		G	
12	R	R	G	-
13	R		G	-
14	R	R	G	-
15	R		G	-
16	R	R	G	-

integral in both modules. When the team combines the results from multiple modules, they should note when a KC has a high integrality rating in both modules.

7.3.4.2.6 Architecture and Integration Risk of Family 3

Family 3 has a distinctly different architecture than the other two families based on the KCs that are contained completely within the bay module, and the different mapping involved in several of both modeled and unmodeled KCs. Decompositions I and J within the family are distinct. KCs 1, 6, 7, and 11 are examples of KCs that are dispersed quite differently within the bay module. For KC #6, there are four PKCs for weapon bay door hinge line alignment, one PKC for each hinge line (see Figure 7-59).[21] This KC is simplified in decomposition I, where each PKC is delivered in two components of one sub-assembly, relative to decomposition J, where it is delivered in the two sub-assemblies of the bay module.

For decomposition I, the integral KCs in the bay module are 1, 2, 4, 12, 16, and the unmodeled KCs represented by the red dot. For decomposition J, all KCs in the bay module are judged to be integral, the ones for I plus KCs 6, 7, and 11. In the upper module of decomposition E, KCs 2, 12, and 16 are integral. KCs 2, 4, 5, 8, 12, 13, 14, 15, and 16 are integral in the upper of G.

To estimate integration risk, two main assumptions were made:

- each module will be designed and built by a different team member, and one of the mid sub-assemblies is likely to be outsourced also (the same supply chain scenario in all cases).
- four technology scenarios are considered: an aggressive process for assembly in the bay with each of the technology scenarios in the upper of E and G as those discussed above, and the same for a conservative process for assembly in the bay.

Table 7-13 shows a matrix of the high and medium integration risk integral KCs for the upper and bay module choices in family 3, with each technology option for the bay listed. Note that KCs deemed integral in both the mid and upper are marked with a '*'.

It is interesting to note that when the upper module of decomposition E is selected, the choice of bay decomposition and technology does not alter the list of high risk integral characteristics.

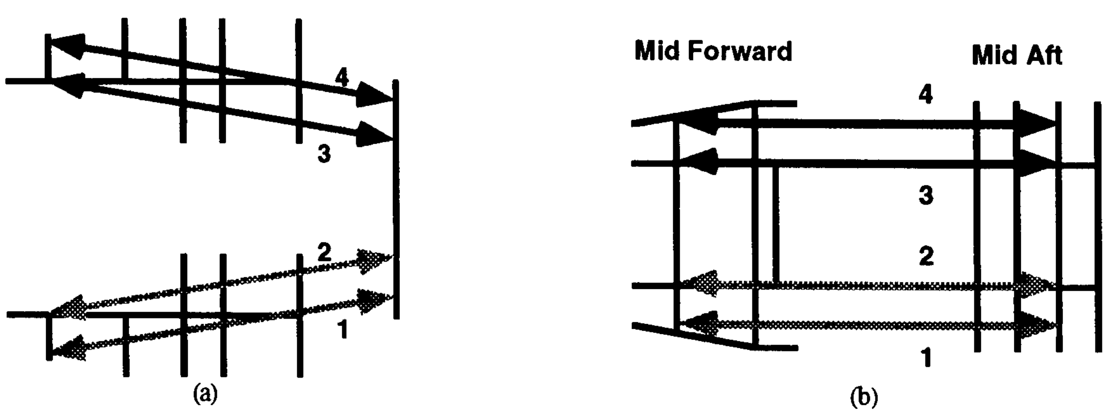


Figure 7-59. PKCs associated with KC #6 for decomposition (a) I and (b) J.

[21] Note in other decompositions these were denoted MKCs because they crossed module boundaries.

Table 7-13

High and Medium Integration Risk KCs for Different Module Combinations and Technology Choices - Family 3

	Decomp I, aggressive bay process	Decomp I, conservative bay process	Decomp J, aggressive bay process	Decomp J, conservative bay process
Upper of E	hi: 1,2*,12,16* med: 4, red dot	1,2*,12,16* med: 4, red dot	hi: 1, 2*, 12, 16* med: 4, 6, 7, 11, red dot	1,2,12,16* med: 4, red dot
Upper of G	hi: 1,2*,4,5,12, 13,14,15,16* med: red dot	hi: 1,2*,4,5,12,13, 14,15,16* med: red dot	hi: 1,2*,4,5,12, 13,14,15,16* med: 6,7,11,red dot	hi: 1,2,4,5,12, 13,14,15,16* med: red dot

However, any choice involving the upper module of G entails high integration risk. This shows the promise of any decomposition of the bay module in family 3, but that additional investigation of the upper module is required to gain the desired architecture insight.

7.3.5 Aggregate Comparison of Concept 1 Candidate Decompositions

Tables 7-14 and 7-15 present an aggregate comparison of the candidate decompositions of concept 1. Table 7-14 lists the 16 KCs, plus the unmodeled KCs represented by the red dot, in the rows, and lists each decomposition studied in the columns. The numbers in the table represent the KC category, which is the same for each in the family. The table shows the integral KCs for each, with the relatively modular KCs blacked out in the table. Just by looking at the table, we see that decompositions B, C, I-1, I-2, and J-1 are the most modular. Family 3 is the most attractive overall because it appears to have the greatest possibility for identifying a decomposition with a relatively modular architecture.

Table 7-14

Aggregate Comparison of the Integral Characteristics of Each Decomposition

KC	B	C	D	E	G	I-1	I-2	J-1	J-2
1	3	3		3	3	3	3	3	3
2	4	4	4	3		3	3	3	3
3					2				
4	1	1	1	1	1	1	1	1	1
5	2	2	2	2	2		2		2
6	1	1	1	1	1			2	2
7	1	1	1	1	1			2	2
8	4	4	4	4	4		4		4
9					4				
10									
11	1	1	1	1	1			2	2
12	1	1	1	1	1	1	1	1	1
13	2	2	2	2	2	2	2	2	2
14	1	1	1	1	1	1	1	1	1
15	2	2	2	2	2	2	2	2	2
16		N/A	?	3	3	3	3	3	3
●	2 or 4	2 or 4	2 or 4	2 or 4	2 or 4	?	?	?	?

Table 7-15 also lists the KCs. The columns are different decompositions with different technology strategies of varying risk. For example, B-1 and B-2 are both columns of decomposition B, but represent different assembly technology strategies that involve different integration risk. The same is true for C-1 and C-2. E/G is a combination of the two technologies of decompositions E and G; the upper module is that of decomposition E. All I and J decompositions involve the more aggressive technology strategies for those decompositions, as shown in Table 7-13. Each decomposition exhibits a different degree of risk. For example, decomposition family 1 is relatively integral, but it involves less integration risk. Family 3 is relatively modular, but when aggressive technologies are applied, its integral characteristics generally involve integration risk.

From these tables the IPT is in a position to consider integrality and integration risk as a criterion in concept and decomposition selection.

7.3.6 How the Method Would be Applied to a Second Concept

The suitability of different concepts for the company's performance, cost, and strategic objectives could be considered as part of concept selection if the CMM was applied. In the JSF case, the method would be applied in a similar fashion to the delta/canard concept, assuming it were still a candidate for selection. First, the KCs for this concept would be captured, and SKCs would be identified. Next, decomposition families would be created. Then, for each decomposition family, MKCs would be identified and chains captured to identify AKCs. Each candidate decomposition in the families would then be identified. After PKCs are identified for each decomposition, the chain procedure would be applied. The metrics would then be used at the module level, and finally at the product level. Candidate decompositions of the second concept would be used to compare the relative integrality and integration risk of the two.

Table 7-15

Aggregate Comparison of Integration Risk of Each Decomposition

KC	B 1	B 2	C 1	C 2	E	G	E/G	I-1	I-2	J-1	J-2
1	3	3	3	3							
2		[illegible]		[illegible]			3				
3						2b					
4				1	1	1	1	1	1	1	1
5	2	2	2	2	2	2	2		2		2
6	1	1	1	1	1	1	1			2	2
7	1	1	1	1	1	1	1			2	2
8	4	4	4	4	4		4				
9											
10											
11	1	1	1	1	1		1			2	2
12							1	1	1	1	1
13	2	2	2	2	2		[illegible]	2	[illegible]	2	[illegible]
14			1	1	1	[illegible]	[illegible]	1		1	
15	2	[illegible]	2	2	2	2	2	2		2	
16					3	3	[illegible]	3		[illegible]	
●	2 or 4	2 or 4	2 or 4	2 or 4	2 or 4	2 or 4	2 or 4	?	?	?	?

7.4 Utilizing the Architecture Insight

The architecture insight provided by the chain analysis does not end at concept selection. Both prior to and after concept and decomposition selection, this knowledge should be used to address the risks, rationalize the sources of those risks, and ultimately reduce the risk or establish plans for risk mitigation. This section constructs four scenarios for this part of the method based on the JSF case study.

Figure 7-60 shows the chain for KC 1j-1.1.0.3. This is a relatively integral characteristic that would need to be dealt with if either Decomposition J-1 or J-2 were selected. The four scenarios below are discussed in terms of this chain.

7.4.1 Rationalizing the Strategy

The Matrix of Dependency and Outsourcing [Fine and Whitney] discussed in Section 3.3.2.3.3 states that outsourcing decisions should be made based on the relative integrality of the element considered, and the degree of dependency between the prime and supplier. Any element in the chain of Figure 7-60 is an integral element in that it shares in the delivery of an integral characteristic. Because of this, outsourcing of these elements should be entered into with caution.

It is unreasonable to expect that, with an inherently integral product like the JSF, that this entire chain can be in the control of one company. However, each team member responsible for each module can make sensible decisions regarding which sub-assemblies and components should be

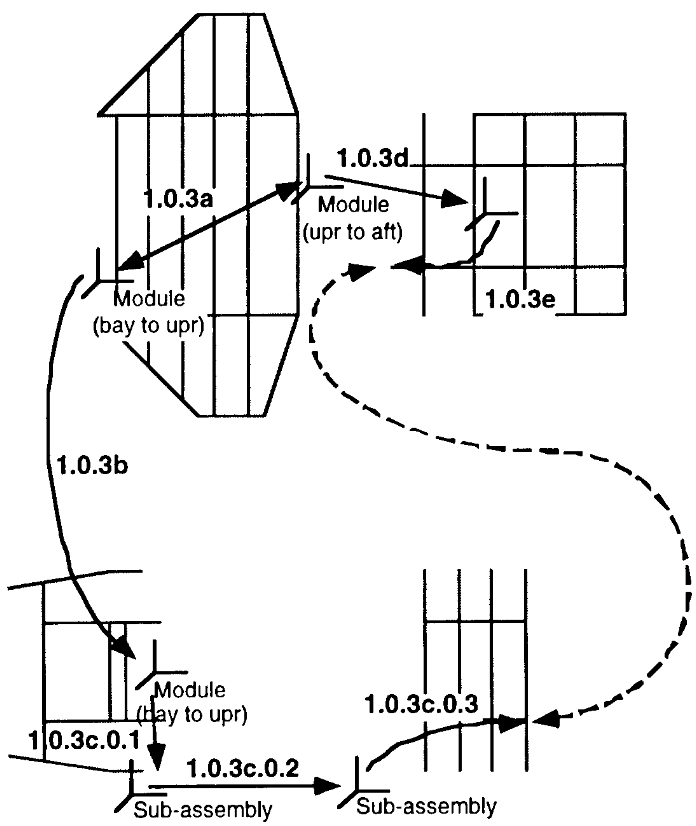


Figure 7-60. Chain for KC 1j-1.1.0.3.

outsourced based on the relative integrality of each element that is an outsourcing candidate. At a minimum, applying the thinking of Fine and Whitney, the prime should avoid complete dependency for knowledge. The prime and its partners should be prepared to develop and produce all elements of an integral chain like that in Figure 7-60, even if the actual production will be outsourced.

Technologies should also be chosen to best avoid integration risk on the most integral chains. It is not likely that the IPT can completely avoid choosing developing technologies on integral chains, but it should be done carefully and the risk should be recognized. If any link on an integral chain like that in Figure 7-60 is to be affected by a new technology, that technology warrants priority when development funding and resources are allocated.

7.4.2 Choosing the Decomposition

Decomposition choice continues beyond the trade-offs at the level of modules and sub-assemblies. As component, parts, and process plans are developed within the selected decomposition, awareness of the effect on integral chains should be made explicit. The DFC becomes a valuable tool when specific assembly and fabrication process choices are made. In the case of the chain of Figure 7-60, each choice will add detail to the basic structure by defining a link in more and more detail. For example, when components of the bay aft sub-assembly are selected and fixturing concept is created, they should be judged based on their impact on link 1.0.3c.0.3 of the chain.

7.4.3 Quantitative Variation Analysis and Tolerance Budgets

With the chain structure in place, the IPT is in place to perform initial quantitative analysis of the high risk integral KCs. The chain in Figure 7-60 shows the information needed to quantitatively assess the integration risk associated with this integral chain. An estimate of the nominal dimension of each link, one or more candidate locating schemes for the elements consistent with the reference frame assumptions, and variation associated with each link for several candidate processes, would be sufficient to perform such analysis. Tolerance budgeting in an incomplete decomposition can begin and assigned to suppliers as part of the requirements for the products and processes they develop. The choice of reference frames is very important. If the sub-assembly and component reference frames in the bay aft sub-assembly can be selected to simplify the chain in Figure 7-60, e.g. if they are assigned to the keels, then the chain can be simplified and integration risk reduced.

7.4.4 Risk Mitigation

As stated above, some organizational boundaries, developing process technologies, or variation uncertainty will be present on any number of chains for integral characteristics in an inherently integral product. The key notion is that the team can do something about these issues if they know about them. Communications between the suppliers can begin early in developing, such as a team discussion regarding the chain in Figure 7-60. The team can make the integral chains a point of integration in every discussion. Developing processes on chains like this will receive priority funding, and their capability can be tested in experiments on articles analogous to the ones on the integral chains. Process capability studies conducted in production ramp up can be

tailored to characterizing the chains of integral characteristics, and compared with the quantitative predictions. All of these activities would represent active mitigation of high integration risk integral characteristics of the product.

7.5 Chapter Summary: System Producibility Analysis Method and the JSF Case Study

The JSF case study affirms two main goals of this research. First, it shows how different decompositions of the same product can significantly change the functional-physical mapping, and with it the architecture and integration risk. Consider how KC #1 is delivered in the three families as shown in Figure 7-28, 46, and 51. Keel alignment is distinctly different in each family. Sixteen KCs were modeled in detail in this way to emphasize how different the architecture can be. In addition, attention was paid to "unmodeled" KCs, specifically how their degree of integrality and integration was likely to change with the decomposition choices. Second, the case study shows that the IPT *can* identify these issues with the limited information available in concept design in a pictorial way using simple sketches. The resulting chains relate decisions made by many IPT members, technical and non-technical, to the integration issues in the design. Significant detail regarding KC delivery and the level of integrality can be attained well in advance of detail design. The chain structure serves as the building blocks for downstream development decisions and efforts that impact the integral characteristics of the product.

Chapter 8 contains a more thorough analysis of the results of this case study.

8. Assessment and Conclusions

This chapter presents an assessment of the research and conclusions. Section 8.1 summarizes the major contributions of this thesis. Section 8.2 assesses the results of the examples and case studies in a point by point review of the hypotheses. Section 8.3 discusses implementation issues and how to apply the techniques developed in this research in other cases. Finally, Section 8.4 presents conclusions on how a focus on integration should be stressed during concept design, and discusses future work required to develop the ideas presented here.

8.1 Contributions of the Thesis

This thesis makes the following contributions to product development research:

- The thesis articulates the need for a design approach that reveals integration concerns during concept design, when these issues are created, and the challenges faced in performing this analysis.
- The thesis addresses common aspects of design theory, systems engineering, and product architecture literature:
  - the thesis explains the reasons for physical domain decomposition and the effect it has on functional to physical mapping, and therefore its influence on architecture and integration risk; this is not reflected in the existing theory, which emphasizes functional domain decomposition alone
  - it clarifies and expands the language used to discuss product architecture types in the matrix of architecture choices, shown in Figure 8-1, as a context for discussing integral characteristics;
  - chains are related to the theory as a vehicle for documenting the function carriers in physical space as well as the basic relationships between them.

		Physical Elements	
		One or a few	Many
Functional Requirements	One delivered by:	Modular Characteristic	Integral Characteristic (chain)
	Many delivered and shared by the same:	Function Sharing	Coupled Integral Characteristics (coupled chains)

Figure 8-1. A matrix of architecture choices.

- The Chain Metrics Method (CMM) shown in Figure 8-2 explains how a multi-disciplinary IPT can concur on concept and decomposition decisions in the context of the accompanying integration issues and risk.
  - For the design team using the CMM, it sets an agenda for concept design decisions that affect decomposition and analyze risk
  - For researchers, the CMM reflects real product development decisions onto the design theory by achieving a map of how decisions made in the physical domain affect the functional domain, and hence the architecture.
- The chain capture procedure is explained:
  - the thesis establishes general principles and rules that maintain established physical and mathematical bases currently used in quantitative assembly modeling
  - the chain capture procedure operates within the constraints of these principles while relying solely on information that can reasonably be expected to be available during concept design.
- The thesis introduces three chain structure metrics used to identify integral characteristics,
  - the Mapping Metric separates two characteristics - span and height - of how a function is carried in the physical elements and their interfaces

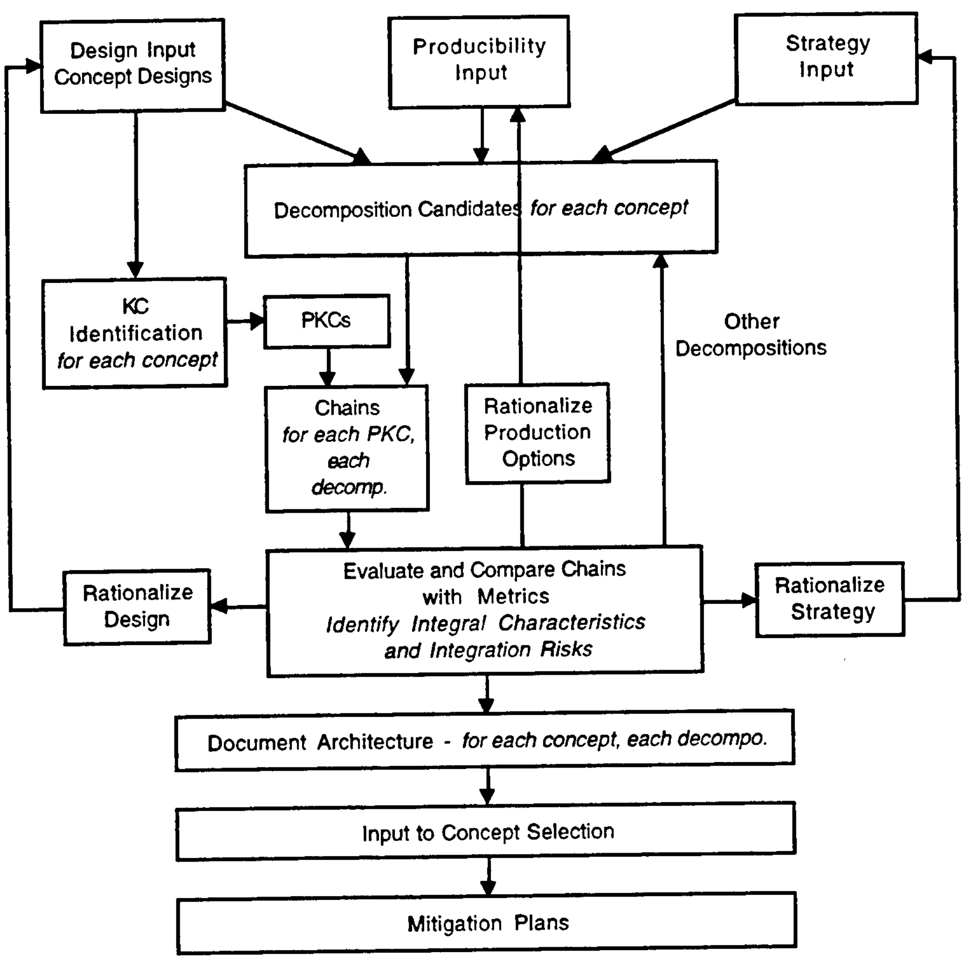


Figure 8-2. The Chain Metrics Method.

    - the Coupling Metric relates how the integrality of a characteristic is altered by the integrality of the characteristics to which it is coupled
    - the Critical Path Metric relates how the integrality of a characteristic is rated based on its influence on the overall assembly cycle time.
- Three integration risk metrics illustrate how to assess integral characteristics on the basis of integration risk, identifying particularly risky situations by measuring:
    - the number of elements on a chain
    - the types of organizational boundaries on a chain
    - the capability and degree of dependency of the technologies on a chain.
- Chains lead to quantitative variation analysis that can be conducted earlier and with an economy of effort.
- The rules for graphical and Interaction Matrix (IM) chain representations explain how the information in chains can be communicated in a multi-disciplinary design team.
- The JSF case study presents an analysis of a highly integral product that explores the issues and tests the method in depth in a highly complex product development scenario; this case study is different from many in the literature in that it investigates such a complex product.
- Several other examples support broad applicability of the findings.

In conjunction with various co-authors, I will produce four short papers from this thesis intended for publication:

- a summary of the conflict between theory and practice regarding physical domain decomposition [Cunningham et al 1998b]
- a description of the CMM and the agenda it emphasizes during concept design [Cunningham et al 1998c]
- a shorter version of the principles, chain capture procedure, and metrics in Chapter 4 [Cunningham and Whitney]
- an explanation of the role played by producibility members of the IPT during concept design, geared toward the aircraft industry audience [Cunningham et al 1998a].

8.2 Assessment of the Results Based on Examples and Case Study

This section critiques the fulfillment of the hypotheses using the two types of analysis discussed in Section 2.3.4 - my assessment based on the examples and case study, and comments from a questionnaire on the JSF case study filled out by LMTAS personnel. I begin with a point by point analysis of each statement of the hypothesis, assessing the results using my analysis and that obtained from members of the LMTAS JSF team. I then summarize the insight I derived from the third analysis approach - broad presentation and discussion of the research in the product development community.

It is important to point out that in product development it is extremely difficult to obtain data on the results and is not possible to repeat an experiment. As in the JSF case study, the real results of any research conducted in the concept phase can not be felt until production, or even later. Measurable results are not possible for many years, and then may be clouded by other influences outside the control of the research. Instead, surveys or case studies must be critiqued based on

their individual results at the time of the study. A combination of such evaluation methods provides some verification. A very conservative approach must be taken when drawing conclusions, and conclusions can only be drawn for the cases studied and where there is clear application in other cases.

8.2.1 Hypothesis Review and Critique

The following reviews the hypotheses based on my analysis and the response from LMTAS. My personal analysis bases arguments on the examples in this thesis and personal observations of these and other product development programs. I support my analysis with two forms of comment from the LMTAS JSF team. First, I interacted with a large number of people in the company to attain a broad cross-section of experience and opinion. Second, I asked several members of the team to answer a questionnaire (see Appendix G). The rationale for the questionnaire is discussed in Section 2.3.4. The questionnaire was answered by the four people who were most familiar with the case study, one member each from design, producibility, technology/supplier strategy, and quality process training/implementation. This is an ideal cross section of the team because they are the disciplines for whom chains and the CMM are expected to define an agenda. In some cases below, I quote these members directly with the letters:

- 'D' for designer
- 'P' for producibility engineer
- 'S' for technology/supplier strategy, and
- 'Q' for quality process training/implementation.

Despite the difficulty involved in drawing conclusions in this type of research, the following review makes a strong case that the thesis supported each point in the two themes of the main hypothesis listed immediately below. The main question that remains is: to what other cases are the results valid? The following discusses the hypothesis point by point, then addresses the main hypothesis at the end and the larger question of broader applicability.

Main hypothesis: A design team's ability to identify the integration issues of candidate concepts will improve with explicit coordination of the many diverse decisions that affect the physical decomposition and hence the product architecture

1. **Chains allow the relative integrality of a candidate concept and decomposition to be estimated by revealing the information needed about architecture: which elements and interactions share in the delivery of particular functions, which companies deliver the elements, etc.**
   a) **chains mesh with existing design theory but also provide a map from decomposition decisions made in the physical domain to their effects in the functional domain that is currently missing in the theory.**
   b) **a procedure for capturing chains can be developed that is applicable to concept design with two properties**
      - **it maintains the scientific basis of tolerance chains**
      - **it includes meaningful metrics that can be applied to the chains for each concept and decomposition to reveal integral characteristics and risks in sufficient detail to aid in evaluating concepts**
2. **A method can be developed that explains how to use chains in a multi-disciplinary design team to evaluate the architecture and integration risk of candidate concepts and decompositions**
   a) **Chains provide a central coordination framework for the team to understand the impact of decomposition options on the architecture, and particularly the level of integration risk that accompanies each option**

b) **chains can be populated with design, process, organizational, and strategic information; the single representation is applicable in all these views of the product to support early design, process, and strategy trade-offs.**

8.2.1.1 Theme 1: Chains as an Indicator of Architecture

The first theme investigated was the following:

1. **Chains allow the relative integrality of a candidate concept and decomposition to be estimated by revealing the information needed about architecture: which elements and interactions share in the delivery of particular functions, which companies deliver the elements, etc.**

This theme of the main hypothesis was supported in the JSF case study because in each candidate decomposition, the delivery of KCs as carriers of function was mapped to the elements and interactions. The "relative integrality" was shown for nine JSF decompositions, and distinct differences were found in each. An investigation of a second concept, such as the delta/canard concept discussed in Section 7.2.3.2, would have revealed equivalent properties for that concept. Further, the chains in several examples were used to indicate the suppliers, technologies, etc. associated with the delivery of each KC, and hence each function.

In their questionnaire responses, the LMTAS personnel show that they recognize and appreciate the utility of a chain study at the concept and decomposition level. Specifically, two members of the team stated that the information revealed by chains is valuable because it can be used at a high-level of decomposition. The members do not want to have to investigate the problem at the part, or even component, level during concept design. Rather, the most valuable analysis for their needs in concept design is at the high levels of decomposition - systems and modules - which is exactly where chains were tested in this case study. In addition, each respondent stated that the chains reveal how the KCs are delivered differently in different decomposition of the concept investigated.

Both in the questionnaire answers and in many conversations with other LMTAS employees, there was a strong sentiment that chains did not reveal problems that until now went completely unrecognized. Instead, chains provide a structured approach to recognizing these issues and explaining them more completely so that they could become a consideration in the debate that surrounds decomposition. According to D (2f/2h)[1]: "The concerns and problems have always been there, but without chains, there has not been a clear method to communicate the concern....The most valuable kind of information that the chains method provides is information itself, an insight into the relationships at a high level. The impact of decisions on the various relationships has been difficult to present in the past."[2]

8.2.1.1.1 Two Sub-points to Theme 1

The first sub-point addresses design theory's depiction of mapping and decomposition:

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[1] Each time I quote the LMTAS survey, I will refer to the question to which the quote was associated.

[2] Note that I interpret the word relationship in this quote to refer to that of decomposition desires that evolve from producibility analysis and their impact on the performance of the product.

a) **chains mesh with existing design theory but also provide a map from decomposition decisions made in the physical domain to their effects in the functional domain that is currently missing in the theory.**

This point was demonstrated by the fact that different decompositions of the same product were shown to have different chains in each case in the JSF case and in several examples of Chapter 5. The chains explain how the functions are mapped to the physical elements, hence the different chains for different physical decompositions indicate the functional-physical mapping. The effects that decomposition decisions made in the physical domain have on function were clearly revealed.

The LMTAS JSF team members were not asked questions regarding this point of theory, but were asked questions designed to find out if they 1) recognize a direct relationship between KCs and the functions they affect, and 2) felt that the chain procedure is an accurate method for mapping how those KCs as function carriers were delivered in physical space. The answers to these questions and in my overall interviews show that they are very comfortable with this thinking, and agree that the chain procedure is a structured way to investigate how the KCs are achieved. According to Q (2a): "I think the most valuable outcome of completing a chains analysis develops when the participants understand how manufacturing breaks [decomposition] affect the performance of the product." Clear in this statement is traceability from function to the content of the chains. They also felt that chains provide a means to plan, i.e. control, how KCs are to be delivered by using this information to choose a decomposition, rather than just a means to react to how KCs are delivered in a given decomposition.

I interacted with many members of the team from the producibility disciplines, so their opinion is reflected heavily in the survey. Each member of the team stated points similar to that made by S (4b): "Anytime that a Manufacturing Engineer can quantify or qualify his likes or dislikes, the more likely an Engineer is going to listen to him." The quote in Section 8.2.1.1 from D is also relevant to this discussion. In the context of the argument of this thesis, the two disciplines make decisions in different domains that influence each other in ways that are not always clear. When a decomposition decision is made by a producibility engineer, chains help explain in a structured way the impact that physical domain decision has on the function of the product. And from my experience with the LMTAS team, the chain language reduces frustration on both sides. The producibility engineer wants to make a structured argument for what intuitively concerns him. The designer, who is tasked to meet many competing needs, wants to incorporate producibility concerns. But chains are needed to provide a language.

The second sub-point deals with the creation of a chain capture and analysis procedure with metrics:

b) **a procedure for capturing chains can be developed that is applicable to concept design with two properties:**
- **it maintains the scientific basis of tolerance chains**
- **it includes meaningful metrics that can be applied to the chains for each concept and decomposition to reveal integral characteristics and risks in sufficient detail to aid in evaluating concepts**

The procedure described in Chapter 4 carried the physical and mathematical chain basis introduced in Section 3.3.3 forward from the quantitative assembly models used downstream in detail design into the concept design phase where decomposition is incomplete and there is limited information regarding geometry, reference frame assignments, locators, etc. A set of principles and rules was developed that maintains the basis to ensure the procedure is subject to the same rigor as existing assembly modeling techniques. The consistency of the principles is exemplified by applying them to the known chain for the C-17 Nacelle. The procedure, validated in other examples, was systematic, repeatable, and based in science. Meaningful metrics were suggested and tested in each example and in the JSF case study. The metrics estimated differences in the integration risk of different decompositions that could be sufficient for evaluating different candidate concepts.

Comments in the LMTAS questionnaire responses provided a mixed review on this point. Regarding the chain procedure itself, the team is very comfortable with the idea, appreciates the fact that there is a basis for capturing chains, and in cases have begun to use it. Several quotes support this, including:

- D (4b): "The chains are related to a scientific basis through the definition of the logic path. It doesn't provide the specifics, like this +/- 0.005" tolerance on this hole relates to the engine being out of alignment by 0.002", but it provides the path through the woods, with the map of what trees to look at."
- Q (4c): "Coordinate transforms and variation control are plenty 'scientific' for producibility studies."

The discussion above regarding point 1a is also relevant here. The team sees the value in the ability of a producibility engineer to state a structured argument that can be formulated in the context of an incomplete decomposition. The technical basis is necessary so that there is a rigorous basis for the content of the chains, and the basis is appropriate in that it is not so overwhelmingly complex that it will confuse different members of the team.

The same can not be said for the metrics. The team is not comfortable with the metrics. They clearly understand how they fit into the method: as a way of evaluating the chains for an aggregate comparison of different concepts and decompositions. Different individuals understand different metrics, such as the issue of coupling and conflict, interaction with the critical path, and organizational boundaries. However, the individual metrics and the scoring system used to illustrate their use were not convincing. I feel that one explanation for this is a lack of familiarity. Prior to the questionnaire, the team had only seen the results of the metrics as opposed to working examples. Unlike the chains themselves, which I had explained and discussed with many team members for some time, the metrics were tested relatively late in the study and only the results were shown to the team. The team did not receive from me a step by step explanation of the metrics, so their value and content may not have been sufficiently understood.

The team appears quite comfortable with the utility of chains for supporting quantitative analysis sooner than they anticipated that such analysis could be accomplished. Prior to my study, quantitative variation analysis was seen as a far downstream activity. However, all agree

that chains can help bring this quantitative analysis forward in the process. There is a mixed opinion regarding whether or not the qualitative information is more valuable in the concept phase. I argue that it is more valuable because all the information needed to do the qualitative analysis is already there, and there is mixed agreement on this point in the responses. Because there is disagreement between myself and some members of the LMTAS team regarding the validity of the metrics, I include as a recommendation for future work an on-going development of these and other architecture metrics.

8.2.1.2 Theme 2

The second theme investigated was the following:

2. **A method can be developed that explains how to use chains in a multi-disciplinary design team to evaluate the architecture and integration risk of candidate concepts and decompositions**

Each example and the case study involved multi-discipline influences on the decomposition. So, while the formal CMM was only applied and tested rigorously in the JSF case, in fact the underlying framework built around chains for a multi-disciplinary debate of the architecture is present in every example as well. I feel the thesis is thorough in describing the trade-offs involved in this type of debate in many cases, and is therefore widely applicable.

The facts that I was involved with people from numerous disciplines in the course of the JSF case study, and that the detailed questionnaire included affirmative responses from members of several disciplines, strongly supports how the method talks to the issues of each discipline. One comment by Q (2b) captures the feelings of many people that I have come across over the course of my research: "...the chains/system architecture perspective...adds a formal set of steps that achieves the elusive aim of cross-functional IPD interaction." In addition, P states that KCs were a major factor in the decisions made to date about the JSF decomposition, with the insight from chains being important to their understanding of the ways KCs are shared among the modules and sub-elements.

8.2.1.2.1 Two Sub-points to Theme 1

The first sub-point addresses the coordination of decisions among the many disciplines:

a) **Chains provide a central coordination framework for the team to understand the impact of decomposition options on the architecture, and particularly the level of integration risk that accompanies each option**

In the examples and the case study, I emphasized that the decomposition selected would likely contain some level of integrality and some degree of integration risk. It is important that the team understand which decisions create the integrality, rationalize those decisions, consider options, and then document the results as part of the concept choice. Because chains indicate what is integral, they were shown to be a framework around which these trades and discussions regarding decomposition could be formed.

In their questionnaire answers, P and D both emphasized points along these lines. They explain that chains are unlikely to be <u>the</u> deciding factor in either the concept or decomposition choice.

Rather, chains reveal the impact of the decomposition choice. According to P (2c/2e): "The intent is to allow ALL IPT disciplines to understand how the overall aircraft decomposition will/will not affect an aircraft KC" and "we realize that if we were truly decomposing the aircraft based on KCs alone then we would have [a different decomposition than the one selected, with] a less complex KC chain structure but a detrimental [performance] implication. Presently we have taken a position where [other factors] have a greater decision making grade than KCs. Our goal is to document and understand the KCs which result from the decompositions." According to S: "Chains will help identify key areas that the prime contractor, teammate, sub-contractor, and the government must recognize as critical."

The second sub-point explains the broad ways to populate chains to communicate across the disciplines:

b) **chains can be populated with design, process, organizational, and strategic information; the single representation is applicable in all these views of the product to support early design, process, and strategy trade-offs.**

Again, each form of information was populated in the chains and the examples. Consider the mapping of suppliers on the chain of an integral characteristic and the discussion of the Matrix of Dependency and Outsourcing in Section 3.3.2.3.3. When the suppliers are selected for delivering the elements of an integral characteristic, this is a scenario where there is dependency for an integral element of the system. This is a high risk position, as indicated in the second risk metric. The chains in the examples indicate such issues explicitly.

This illustrative and communicative nature of chains was recognized by the LMTAS JSF team. According to S, who is intimately involved in the make/buy decisions of the team (3d): "From a Strategic Sourcing point of view, the earlier we can define the chains and how they relate to Key Characteristics, the better our make/buy decisions will be." Also clear in the comments, especially regarding the need for quantitative analysis, was the manner in which chains form the structure for making process and capability choices with a known impact on KCs as carriers of functions.

8.2.1.3 Main Hypothesis

With all the sub-points of the hypothesis strongly supported by the case studies and comments from LMTAS, I am now in a position to discuss the breadth of applicability in the context of the main hypothesis.

Main hypothesis: A team's ability to identify the integration issues of candidate concepts will improve with explicit coordination of the many diverse decisions that affect the physical decomposition and hence the product architecture

Like all aspects of this research, this hypothesis is true in any product whose physical decomposition has an impact on the architecture, and in turn raises integration risk. Conversely, in products where the delivery of key functions is not substantively altered with a different physical decomposition, this hypothesis would not be applicable. A resounding theme from the LMTAS comments is valuable here: people who are smart about product development are

already thinking about architecture and integration issues, so the "spirit" is already in place. What my research articulated was the decisions that demand the team's attention in order for them to recognize integration issues and communicate them widely among the team. The statement in the main hypothesis is broadly applicable to products where integration is an important issue. According to D (4a/2f): "...chains certainly have a place in concept design. Chains should be included as soon as possible, as soon as two alternate concepts are being evaluated where the tolerance/key feature control potentially crosses component boundaries."

The main hypothesis is important because some representations in design theory and systems engineering/architecting imply that architecture is completely in the control of one or a few members of the design team. My research shows that such a view underestimates the complexity of the process of creating an architecture. Architecture is in fact affected by many decisions made by many members of the team. The team's ability to identify and explicitly control the architecture improves when all these decisions that affect the architecture are emphasized in the context of architecture. Particularly, my research shows that physical domain decomposition decisions have a powerful effect on architecture. My work shows how to coordinate the decisions that create the physical decomposition, and hence influence the architecture.

Recall that in my discussion in Chapter 2 where the hypothesis is introduced, this main hypothesis evolved from a working hypothesis on chains alone. Recall further that I found that in order to identify integration issues, a team requires an explicit identification of the functional-physical mapping - the product architecture. And, to identify the architecture, I investigated what types of decisions create the architecture. The physical domain decisions were found to be a key missing component of the theory and to have substantial impact in the creation of the architecture. Because my work relates physical decomposition decisions to integration risk, the main hypothesis has been proven in cases where the chain approach itself is applicable.

8.2.1.4 Counter Hypothesis

Counter hypothesis: a design team's ability to identify the integration issues of candidate concepts will *not* improve with explicit coordination of the many diverse decisions that affect the physical decomposition and hence the product architecture.

The counter hypothesis is disproved by the cases and examples of the thesis. This means that while the hypothesis is not known to be true in all cases, the counter hypothesis is known to be false.

8.2.2 Broader Assessment from Academia, Industry, and Government

My research was shaped and supported by a broad perspective on product development attained from the opportunity I had to widely discuss and publicize my progress and results. Appendix A lists interviews and presentations conducted to attain this necessarily broad perspective. The broader review provided an informal basis on which to base my conclusion that all aspects of the hypothesis have been supported in this thesis. Uniformly, the major themes of this thesis have been supported in these discussions. Further, the importance of work in the area of integration and in the early phases of design were found to be critical.

The broader assessment had its strongest impact by forcing me to check assumptions as I proceeded, and to seek meaningful validation of the results. The types of assumptions that were tested included whether I was considering the problem from one viewpoint or many, that I thoroughly understood and critiqued existing literature and practice, and that I was testing all my claims in real industrial settings. It was stressed to me that validation be included in the form of different companies, products, and opinions rather than from just one example. So, while the JSF case study is the foundation for much of this work, I have set out to be thorough in considering other examples and in discussing the results widely with people experienced on different products.

8.3 Applying the Method: Implementation Issues

This section discusses how the CMM developed in this thesis can be applied in future research and other real product development programs. Four topics are covered: mechanics of the method, required participation and skills, data structures and tools, and measures of progress.

8.3.1 Steps to Apply the Method to Other Cases

The framework of the CMM shown in Figure 8-2 is the basis for any application of my research. In addition, the chain capture procedure, rules for the graphical depiction of chains, and metrics described in Chapter 4 are also universally applicable when applied to the intended class of problem.

The process followed in the JSF case study has three distinguishing characteristics:

- it conducts the execution step of the CMM in phases that match how the organization is assigned to the physical elements at various levels of the decomposition hierarchy
- it develops KC terminology, specifically names for different types of PKCs, and
- is applies the metrics at the module level and then at the system/product level, again matching how the organization is assigned in the hierarchy.

Recall the rationale for tailoring specific aspects of the method. The chain capture procedure was segmented to reflect the team arrangement. The KC terminology was selected to clarify the level of integrality associated with each type of KC; e.g. that the presence of an SKC indicates that more than one system delivers the KC. Finally, the application of the metrics at the module and then system level also reflected the teaming arrangement and how priorities should be identified and elevated.

Two principles should be followed to ensure success in applying this research. First, the physical and mathematical basis of chains, captured in the rules for the chain capture procedure, must be maintained to ensure accuracy of the chain structure. The procedure is relevant to requirements that are delivered in physical dimensions of the product. Second, the method must represent the drivers of physical decomposition to ensure the proper members of the team that influence integration issues are involved. Beyond this, there is latitude for applying the method to a particular application. Besides the tailored aspects shown here, others may take the form of additional metrics to reflect unique integration risk contributors, teaming arrangements different from the one encountered in this case study, etc.

8.3.2 Required Participation and Skills

The CMM casts IPT members in an environment that is unlikely to resemble their current environment. IPT members often remain in a stovepipe environment even when assigned to a dedicated team. The method presented here forces them to work through an integrated agenda to capture, assess, and document the architecture and integration risks. This approach requires the following new forms of participation and training.

8.3.2.1 Engaging Team Members

The fundamental issue regarding team arrangement encountered in this research is that the CMM casts producibility and strategy team members as equal participants in design and selection of the product architecture. This is different than the typical "design for" paradigm that casts producibility and strategists in a watch dog role; i.e. as looking over the shoulder of the designers and saying, "don't do this." All members of the team who must influence decomposition in order to achieve an architecture that meets their goals are part of actively shaping the architecture, and must be engaged in the process as equal members.

In an environment where one discipline dominates the product development organization, this issue could require a different leadership approach to allow for architecture trade-offs. The leader must recognize the equal weight that technical, producibility, and strategy issues share, and foster active trade-offs among them. To make this happen, common language and common frameworks like chains must be established to communicate across the disciplines and achieve the concurrence sought.

At LMTAS, as in many defense companies, design tends to dominate the product development organization. This is a carry-over from the era where performance optimization dominated, and is not unique to defense industries. It is not surprising that the many producibility engineers with whom I interacted saw chains as a tool for their use, to communicate their concerns to design. A broader view indicates that the tool is meant for team coordination, and some type of integrator may be needed. According to Q (5a): the process requires "a few chains/variation risk 'experts' who can be loaned to IPTs..." This speaks to the fact that chains tend to emphasize a knowledge that is not common in product development teams, and is integrative in nature.

This integrator will need to combine three skills. First, the person requires a system-centric view that includes a level of comfort with the idea that single functions are often dispersed among many physical elements of the product. Second, the person requires a level of comfort with the underlying basis for chains. Third, the person needs to be an integrator in that he/she can communicate across the boundaries of individual disciplines. Integrators such as this are not likely to be found in large supply, or it is likely they would already be pushing the agenda I have developed here. Rather, such persons need to be cultivated.

8.3.2.2 Training

Few members of the team need in-depth training for the CMM to work, but it is clear that the CMM emphasizes important issues regarding system-centric thinking and integration that are not well understood. Therefore, the method requires, at a minimum, training in the meaning of the

goals, concepts, representations, metrics, and organization of the method so all IPT members understand the agenda and the purpose of the analysis. The mechanics of the chain procedure should be limited to design and producibility members, as cast in the CMM. However, the results must be shared widely in graphical representations like those in this thesis that can be understood by all members of the team.

LMTAS has begun a program to communicate the meaning of chains among members of the design team. The training begins with a short overview that explains the basis of chains and examples that show different chains for different decompositions of a product with which the team is familiar. For this purpose, LMTAS found the DFC to be the proper starting point, because sufficient information was available in the example to use that tool. Their goal is to test the ideas on smaller articles that are closer to production than an entire airframe in the concept phase, and with it develop processes and teaming arrangements that work. The tool would then be translated to larger development programs. When applied earlier in product development, a transition away from DFCs, which contain information that is not available during concept design, to graphical chains will be required. There is wide agreement at LMTAS that some level of management training is required for the idea to gain support and to become part of the mainstream development process.

8.3.3 Data Structures and Tools

To foster a focus on integration issues, product data models must capture integration information that explains how any physical element shares in the delivery of KCs with other elements. I have yet to find a tool where interactions among physical elements in different branches of the WBS could be represented based on their shared delivery of product function. Rather, systems engineering tools with which I have basic familiarity tend to parse a requirement out from the top and allocate portions into different branches. In order for the interactions like those found in chains to be captured and populated, a data structure must be in place that can store this type of information.

At a minimum, the data structure requires a tabular construction that relates a physical element not only to its partners in a branch of the hierarchy, but also to its partners in the delivery of KCs who may reside in any branch of the hierarchy. Many assembly modeling packages now contain information about the physical hierarchy, often called the Structured Bill of Materials. However, the data provided by chains is required to fill the latter table where an elements role in shared function delivery is captured and displayed.

One means to achieve an integration capability in product data models is to follow the model suggested by Hatley and Pirbhai, shown in Figure 3-15. Recall that the two different elements at the second level of the structure distinguish between flows and physical interfaces. The Architectural Flow Diagram (AFD) captures the information flows between physical elements, while the Architectural Interface Diagram (AID) captures the physical interfaces between the elements.

Figure 8-3 draws analogies to the information communicated in chains. The top level block is the physical hierarchy. During concept design, different candidate hierarchies are created as

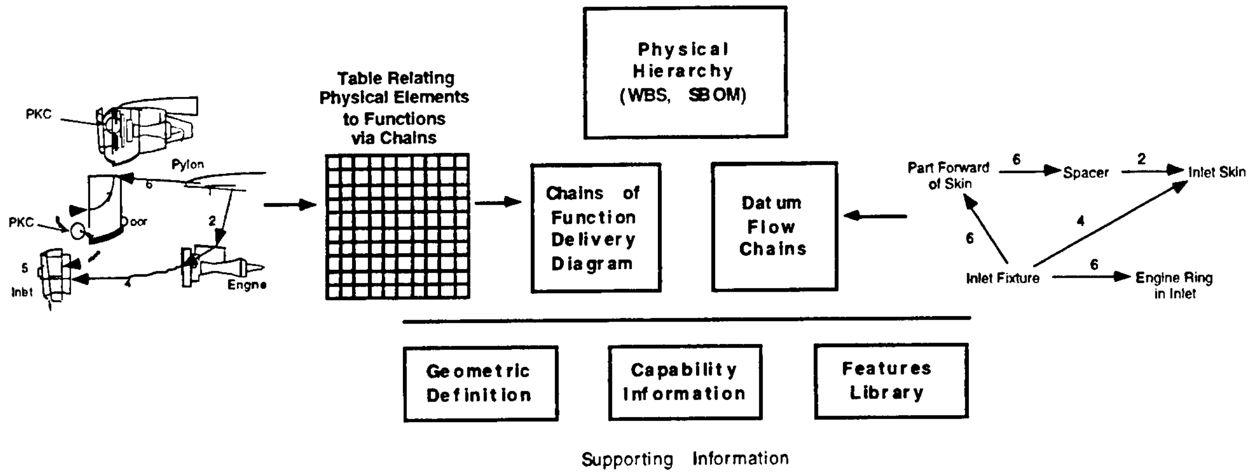

Figure 8-3. Analogies between the Hatley/Pirbhai data model and chains.

candidate decompositions. Chains communicate how elements share in the delivery of a function. This can be thought of as how function "flows" through the finished product based on the way it is decomposed and assembled. This would be captured in a Chains of Function Delivery Diagram akin to the AFD. The detailed information that supports a formal analysis of the chains describes the physical features that serve as locators at each stage in the assembly process, and the tolerances among these features that can be used to represent variations in transforms; this describes the reference frames. This information would be captured in a set of Datum Flow Chains akin to the AID. These two diagrams would evolve the same way the information does in the CMM and follow-on design activities: the chain structure comes first, while specific reference frame assignments and locator choices come with the more formal DFC analysis after the concept and decomposition are selected.

In addition, tools to enable the CMM are needed. Suggestions for CAD tools related to the chain procedure are discussed for future work in Section 8.4.2.4.

8.3.4 Measures of Merit

For the method to gain acceptance as a part of product development processes in industry, it requires management tools. Two types are required. The first is a set of measures to assess progress of the team in performing the CMM. The LMTAS JSF team members that I worked with closely recognize the value of the approach but know from experience that "culture, time, and schedule pressures" impede good ideas from taking root. For this reason, they feel that proof in a smaller product setting will form a basis for translating chains into broader application in the company. In this smaller application, progress measures could be developed for how the team is attaining the required knowledge about architecture and integration risk, consideration of alternatives, and documenting their findings so that the control of KC delivery is attained.

The second type of tool required is that needed to justify its use, such as a Return on Investment (ROI) anticipated by executing the method. The basic structure of any such tool is the value of a non-recurring up front expense measured against recurring savings downstream, both in the nominal process and in re-work and corrective actions. This presents a significant challenge because it is often difficult to calculate the cost or time penalties of poor integration in existing

products due to incomplete data bases on the problems faced. According to D (3I): "Once trained, it doesn't appear that it should take a significant amount of time to work through a [concept]. It is probably additional time since there doesn't appear to be a similar current process. Downstream time savings are likely to be had because it may save the trouble of having to do some detailed producibility/assembly studies on some non-competitive concepts." Some team members also feel that the CMM and chains procedure need to be "simplified" and "integrated" with other analyses. Again, an ROI is likely to be recognized after testing on a smaller article.

8.4 Conclusions and Future Work

This final section draws conclusions on what chains indicate about product development, and discusses future work to develop the ideas further.

8.4.1 Conclusions: What Chains Tell Us About Development Strategy and Integrated Product Teams

This thesis draws focus to concept design and integration issues, and calls for an industry and academia focus to leverage a great opportunity for competitive advantage. The following draws conclusions on what this research indicates about the importance of an integration focus during concept design.

8.4.1.1 Concept Exploration Phase and Milestones

In order for integration to receive the attention that it deserves during concept design, one needs to accept that integration problems and risks are born in concept design decisions. This thesis articulated how concept selection, which includes at least some high-level decisions about the product decomposition, is the major milestone of concept design. The architecture decision happens in concept design, consciously or not. If the design team is to influence the architecture, they must systematically analyze the choices or be stuck with the one that results from other decisions. In order to achieve the proper focus, architecture and identification of integration issues and risk must be universally recognized as milestones that are achieved as part of concept selection.

8.4.1.2 Interaction of Government Program Office and Contractor in Defense Acquisition

The Government Program Office acts as the judge of suitability of the selected concept to achieve the customer needs with acceptable cost and risk. As described in Section 7.2.1, there is an analogy in commercial companies where project approval is based on some milestone. In order for suitability of the architecture to be judged for its sufficiency and integration risk, the approving authority must prioritize an assessment by the design team.

In the case of the Government, the program office plays a role in the architecture process. At a minimum, they must be aware of the role they play and understand the impact they have on decomposition, the teaming arrangement, etc., and the impact on integration risk. As discussed in the participation and skills section above, the Government participants do not have to know the

mechanics of chain procedure, but must understand the meaning, representations, metrics, trade-offs, etc. as well as any other participant that impacts the architecture.

In the case of a defense program, the Government plays two other key roles. First, they define the award criteria that are to be used, and with these criteria set the priorities that will be followed by the contractors. If architecture and integration risk are not part of these criteria, they will not receive the necessary attention at the important time - during concept design - and the opportunity to have an influence will be lost. In addition, because the Government typically determines the program schedule, they determine the degree of schedule pressure under which priorities will be set. If excessive schedule pressure is set, prioritization of some analyses will result in others not being accomplished prior to the required milestones. In these two activities, the Government actively shapes the integration risk that will have to be dealt with through the remainder of the program, and therefore should be aware of the impacts in how these decisions are made.

8.4.1.3 Interaction in the Tiered Technology Supply Chain

Chains are a living element of the product, carrying intent throughout the development process and providing traceability to early decisions. The chain structure born in concept design is the basis for carrying this information through all subsequent phases. Figure 8-4 shows, in the context of Deming's Plan-Do-Check-Act quality cycle, the role chains can play in each phase of product development. Beginning with concept design, chains are captured, analyzed, and passed through the organization and supply chain so all IPT members can clearly trace how they impact KCs in the selected concept and decomposition.

The definition of the chains matures along with the product definition - the geometry, process specifications and capabilities, and supply chain. The chains structure, coupled KCs, and AKCs are passed as part of the concept design into the detail design phases. Early during detail design, the chain is used to choose datum structure, assembly sequence, mating features, and the locating scheme in assembly, which can all begin prior to part-focused detail design to create a top-down design process and improved quantitative variation analysis based on DFCs [Mantripragada]. In

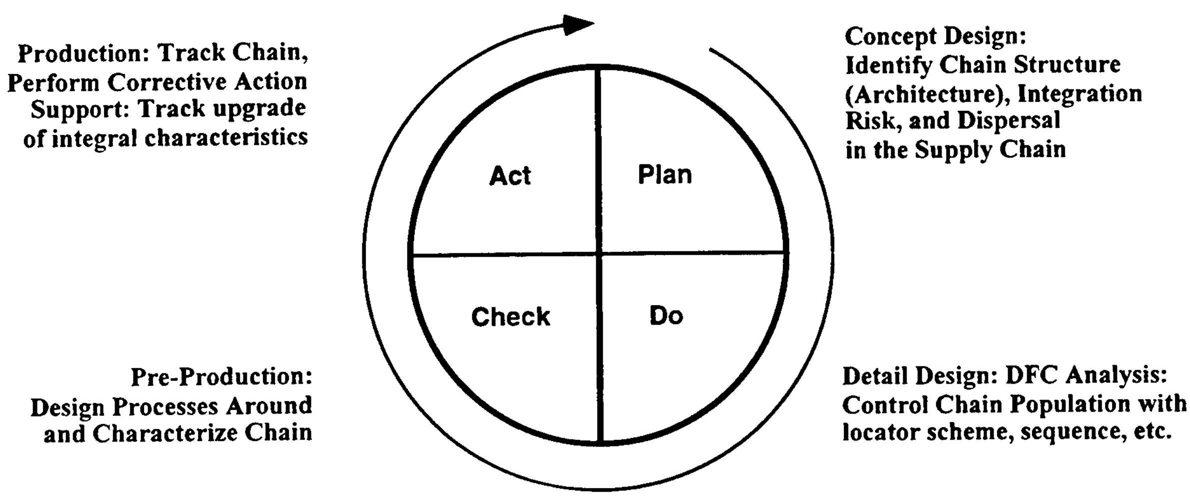

Figure 8-4. Chain use in all phases of product development.

addition, Demonstration/Validation Phase process and technology development activities and supply chain alliance priorities are identified in cases where process development occurs along with product design. The priorities would be set for the processes involved in delivering high risk integral KCs.

From the detail design phase the fully developed DFCs are defined and can be analyzed quantitatively. The graphical chain depiction continues to play a role as a communicative tool in the dispersed supply chain. In production preparation, chains guide process planning and development, process capability verification, fixture design, and manufacturing planning [Cunningham et al 1996]. In production, chains are used both in implementing a measurement and reporting plan, and in guiding a diagnostic root cause analysis process when quality problems occur to prevent re-work from creeping into the mainstream process. If quality problems occur for a non-KC, i.e. for a system feature whose chain was not captured as part of the initial design process, the chain for this feature can be readily captured and used to guide statistical process control data gathering and analysis to solve that problem [Cunningham]. Finally, during support and product upgrade, chains provide an indication of how these activities will alter the integral characteristics of the product. By identifying these issues prior to upgrades, a proper assessment of the complexity of analyzing and implementing the changes can be conducted in advance.

In all these phases the underlying themes are the same. Chains define the roles of all parties and trace key customer deliverables through the WBS, supply chain, and development process in each phase of product development. The LMTAS JSF team members recognize how chains can be a useful form of documentation that will avoid duplication of effort when decisions are revisited downstream. In addition, those with shop floor experience envision chains that were created in concept design to be communicated to the production floor ten years from now so that each step in the assembly process can be executed with the knowledge of what KCs it affects, and what other steps share with them this responsibility.

8.4.2 Suggestions for Future Work

This thesis is foundational in that it is equal parts articulation of a problem, development of a method to address the problem, and illustration of the problem via the industrial setting. The thesis supports all parts of the hypothesis, but the ideas indicate the need for a great deal of follow-on work.

8.4.2.1 A Taxonomy for Product Architecture

This thesis includes terminology, metrics, and descriptions of architecture that have the opportunity to mature into a well-developed taxonomy for discussing the important topic of product architecture. Architecture is an extremely powerful characteristic of the product that can tie together disparate decisions about the product. It is pervasive in product development, with decisions throughout the process affecting the architecture, and the architecture affecting decisions throughout. Ulrich and Eppinger [1995] recognized that "modularity is a relative property of a product architecture. Products are rarely modular or integral. Rather, we can say

that they exhibit either more or less modularity than a comparable product..." As discussed in this thesis, the terminology as it stands is insufficient for substantive discussions of architecture.

I originally proposed as part of this research to develop an improved taxonomy of product architecture, but some time ago it became apparent that this would not be achieved. Dedicated research is needed to develop this taxonomy. It is too important a concept to transition to industry to have an immature representation offered that in the end would need updating or an overhaul. Industry and academia both are just beginning to feel fully comfortable with the simple properties "modularity" and "integrality" so a well-conceived, more detailed taxonomy will need both development and well-conceived teaching to be of value.

The CIPD is well positioned for this research and has the development of architecture metrics as a near term goal. The CIPD is expected to be effective in this research for three reasons. First, in its structure it is dedicated to developing the multi-disciplinary communication vehicles needed to support improved IPD in industry; architecture is an important type of characteristic that should be, and is, at the top of the center's agenda. Second, with its many industrial partners, the center can develop relevant companion case studies of highly integral products, like the deep case study presented here, to develop this taxonomy from a larger base of case studies than I or any one individual could. These companion cases could unify the taxonomy among many functional domains. Finally, the members of the center are among the most forward thinking in this area and already bring a wealth of application-based research that could achieve a practical, meaningful taxonomy to industry.

I was successful at establishing the matrix of architecture choices (shown in Figure 8-1) as a framework for this effort. In addition, the JSF case study has revealed many pertinent issues for developing this taxonomy, and this thesis contributed tools (chains and the IM of chains) and measures (six metrics of integrality and risk and the span and height distinctions) that can be used to start this research. In addition, I attempted to articulate the shortcomings of the current discussion when applied to hierarchies. I feel strongly about its further development and fully intend to remain active in this aspect of follow-on research. My strongest recommendation for future research work is that this become a research priority.

The metrics will hopefully evolve into a more suitable global measure of architecture. Ideally this would be quantitative, which could be achieved by applying techniques from graph theory. By considering the mapping of chains on a hierarchical representation of the product, or by the content of the IM, future research could move in this direction.

Whether qualitative or quantitative, the metrics posed in this thesis and future architecture metrics require a great deal of effort in terms of maturity. Broad testing and developing of the metrics themselves, and suitable scoring scales, is critical. This thesis developed some metrics and illustrated the scoring, but this is far from sufficient for such an important measure of the product. Well-conceived metrics must be simple to use and readily understood by all disciplines involved in architecture. When this is accomplished, implementation of architecture-focused design processes like the CMM will have a much greater potential for success, and companies will be much more successful in designing new architectures.

8.4.2.2 Integration Issues in Other Domains

The limitation of chains to the mechanical domain is a major barrier to broad implementation in many of today's most complex electro-mechanical products. While there are a large number of functions that can be delivered in physical dimensions, whose delivery can then be investigated with chains, there are functions in other domains that are not delivered in this manner. The method needs to be expanded with additional tools to identify integration issues and assess integration risk in other domains. The requirements for such tools would be the same as those I imposed on chains: that it be systematic and based in science, not the judgment of team members. This is the most important recommendation for future work related to practical application of the ideas presented in this thesis.

8.4.2.3 Product Development and DTM Research

This thesis articulated several conflicts between design theory and the decisions faced by product development teams involved in creating products that exhibit integrality. The thesis was successful at indicating a way to relate decisions made in the physical domain to the effects they have in the functional domain. The design theory needs to evolve to recognize this approach. This is not a radical leap because this thesis does not tear down the basic structure of the theory: the representation of domains, matrix relationships among the domains, representations of the relationships at levels of the hierarchy, or the goal of achieving a design with minimum risk. The thesis does differ in how the design team traverses the domains and identifies the impacts that decisions have from one domain to another.

The second most important piece of theoretical work is therefore the development of relationships between physical domain tools like chains that the basic structure of design theory established in AD and EQFD. Clarification of terminology and mapping of the elements from this thesis into the larger structure is required.

In all DTM pursuits, it is incumbent upon the research community to emphasize integration issues in the models and guidance that the theories provide to the practicing user. Integration issues represent a particularly challenging type of problem because they cross disciplines, happen early in development, and require people to exercise a skill that is somewhat uncommon: system-centric thinking. It is incumbent upon the research community to take on this challenge because these problems are so difficult to solve and have been neglected both in academic and industrial research in the past. It is the research community's responsibility to take on the tough problems, and this is one of them.

8.4.2.4 Product Data Models

As discussed in Section 8.3.3, product data models must be developed that emphasize integration issues. Tables that relate functions to physical elements based on chains, and that relate physical elements to each other based on DFCs, are two initial requirements.

8.4.2.5 Implementation in a CAD/CAE Toolset

The CMM and chains procedure and scoring will be much more credible when supported by working CAD/CAE tools. This will streamline the analysis in time, and allow the findings to link with other concept design analyses and tools. Some examples of tools that are required include:

- a tool that allows the user to define a decomposition from some electronic models that includes a representation of each PKC's end features, and automatically generates the hierarchy, PKCs, and chain structure
- a tool that identifies coupling and assists the user in identifying conflicts
- a tool that generates representations of multiple chains like an IM
- an associated tool that converts generic chains into chains incorporating different mate options and reference frame (e.g. proximity) assignment choices
- a tool that links chains and a list of pertinent information, such as a candidate supply chains, technologies, and processes
- a tool that guides application of the metrics and reports results
- a tool that links the chain structure created in the procedure, and the candidate decomposition, to a quantitative variation analysis tool like VSA.

All these tools must link members of a hierarchy like a WBS in a dispersed organization. Such tools will be challenging to develop in that they will not be derived from existing or comparable tools. However, the underlying techniques for all such tools are in place based on this thesis, if the correct structure and guidance is enforced.

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Appendix A

Site Visits, Meetings, and Presentations Conducted as Part of this Research

- June-August 1994: Vought Aircraft Company (C-17 Nacelle Study)
- January 1995: Vought Aircraft Company (C-17 Nacelle Corrective Action Study), Ford Motor Company St. Louis Assembly Plant and Dearborn, MI, Body and Assembly Operations (1995 Explorer Corrective Action Study)
- March 1995: Vought Aircraft Company (767 Horizontal Stabilizer Process Re-design Study)
- June 1995: Boeing Company (767 Horizontal Stabilizer Process Re-design Study, and review of latest product development methods on 777 and 737X)
- June-August 1995: Vought Aircraft Company (767 Horizontal Stabilizer Process Re-design Study)
- November 1995: LMTAS (Presentation of research to date)
- December 1995: LAI Factory Operations Group (Presentation on 767 Horizontal Stabilizer Process Re-design Study)
- January 1996: LMTAS (Review of latest product development, supplier management, and organizational methods, discussion with all major development and production programs), Joint Direct Attack Munition Program Office, FL, (Review their approach to cost-performance trade-offs in early design)
- February 1996: Master's Thesis Published [Cunningham] (C-17 Nacelle and 1995 Explorer Corrective Action Studies)
- March 1996: LMTAS (JSF Review), Vought (Final 767 Study Presentation)
- May-August 1996: LMTAS (JSF Project)
- June 1996: 767 Process Re-design Paper Published and Presented [Cunningham et al]
- Summer 1996: Several discussions with Lt. Gen. Ted Campbell, former Director of Requirements for the Air Force end user of the JSF (cost performance trade-offs, priorities, and methods from the customer perspective, gathered his comments on the chain concept)
- December 1996: Mechanical Engineering Department Design Group Seminar (Chains in Concept Design)
- 1997: Intermittent discussions with numerous faculty at MIT and other academic institutions involved in product development research (chain concept, method, rationale)
- March 1997: LMTAS (JSF Project), LAI Presentation (Chains as a coordination tool in Concept Design, presented to Product Development and Supplier Relations Groups)
- May-September 1997: LMTAS (JSF Project)
- May 1997: JSF Government Program Office (presentation of chain method and rationale, discussion with several members), separate discussions with Mr. Dan Robinson, Faculty of the Defense Systems Management College, Maj. Gen. Ken Israel, Defense Airborne Reconnaissance Office Director, and Capt. (Navy) Dyer, Former Director of F/A-18E/F Program (chain method in concept design)

- Summer 1997: Ford Body and Assembly Operations (several discussions on small truck architecture trade-offs)
- July 1997: GRC, Inc., Dayton, OH (Review a concept design tool for cost-process-performance trade-offs called JMCATS, and the underlying methodology)
- October 1997: LMTAS visit to MIT (Project Review), LAI presentation (chains in concept development presented to the full body of LAI), CIPD NSF Review (poster presentation)
- November-December 1997: LMTAS Questionnaire (comments on research results)
- December 1997: MIT Course 2.996, Mechanical Assembly and Its Role in Product Development (one full class presentation of chain method and examples)
- January 1998: Doctoral Defense Presentation and Thesis
- February 1998: LMTAS (Final Presentation), completion of several working papers on this research

Appendix B

A Brief Review of Tools Used to Assess Producibility

This appendix briefly summarizes tools that are currently available to assess producibility. The first section describes Design for Manufacture and Assembly (DFMA) tools as a broad category. The second section describes tools specifically meant for utilization on the Joint Strike Fighter (JSF) program.

Tools to Assess Producibility

In the well-established 2D IPD (design and manufacturing) environment, IPTs developing complex integral products set out as early as the concept design phase to assess producibility and attempt to develop a producible design. This design-producibility interface is enabled with a set of methods and tools broadly called "DFMA." To date a common approach found both in practice (personal observation and those of many others) and in publications has been to apply in concept design methods found effective in detail design phases that are focused mainly on parts and rely on detailed definition of parts [multiple citations]. The pitfall of this practice is that detailed analysis at the system level cannot occur until detail definition at the part level is achieved and can be pieced together to assess the effects at the system level. In order to be effective in concept design, a producibility analysis method must focus first on the system level to study product design concepts with little design detail, perhaps not even a complete decomposition of the product much less any definition of the parts, and must be applied in a dynamic, fast moving environment of evolving concepts and rapid decision-making.

Any tool that relies on detailed design definition is a poor candidate for this environment because the very decisions my work tries to address - those leading to physical domain decomposition - would have to be made and pursued in great depth before meaningful results would come of the analysis. By the time parts are defined in sufficient detail to apply such a method, too much has been invested to consider rethinking the initial decisions like decomposition. Therefore, concept design requires unique analysis tools or new extensions of existing tools, but not an attempt to directly apply existing methods.

Therefore, the critical issue associated with any DFMA tool is the amount of design detail required for its use. DFM is generally described as the incorporation of the concerns and constraints of manufacturing in the design of individual parts, illustrated in the discussions of the concerns for specific fabrication processes [multiple citations]. These tools are clearly not applicable to concept design. DFA is traditionally implemented in terms of part and fastener reduction in favor of fewer, more complex parts to save assembly time and cost, using the Boothroyd and Dewhurst charts to determine parts that can be eliminated [Boothroyd, Boothroyd et al]; this approach is not necessarily always the most appropriate when cost and lead time are included for consideration [Ulrich et.al.]. In both cases, a great deal of detail is generally required for use of these tools, again down to the level of parts and defined interfaces among these parts. Boothroyd, et al and Redford and Chal [1994] specifically state that the

DFA tools developed in their work are not suited to early design phases, so these too were eliminated from consideration for my research.

The goal of Boothroyd's approach is to classify issues in design and provide a repeatable means to compare candidate designs. This approach motivated the chain metrics approach that I develop in this thesis, which seeks achieve a similar type of comparison but to do so with a minimum of detailed information about the candidates.

JSF Producibility Tools

While it is true that cost has not been an equal driver with performance in past defense product development, this is not due a void of producibility analysis tools available in this industry. The types of DFMA tools discussed above have been used in many recent programs during detail design [e.g. Behan]. The DOD has developed a set of producibility measurement guidelines that is available for both program office and contractor team members [NAVSO]. The following describes the tools in this guideline, and then describes a set of producibility tools developed by JSF. Of the JSF tools, I focus on a tool called "Manufacturing Capability Requirements" (MCR) that has similar goals as my CMM. I contrast the two and explain key issues regarding applicability to concept design.

Traditional DOD Producibility Assessments

The DOD guidelines recommend that producibility analysis be part of the development process from the beginning of product development, with emphasis in concept design when there is the most opportunity to affect product cost. The guidelines provide two tools to assess producibility, but fail to provide a framework applicable to the limited product definition present at that time.

The first tool is a universal "Producibility Assessment Worksheet" (PAW). The PAW, shown in Figure B-1, is to be applied to all elements of the system and is used to judge the risk in five categories (and along scales ranging from the following):

- design ("existing/simple" to "highly complex"),
- process ("proven" to "requiring development"),
- materials ("readily available/aluminum" to "18-36 month order/new material"),
- design to cost ("budget not exceeded" to "goals can not be achieved greater than 50 percent of the time"), and
- schedule compliance ("negligible impact" to "major slip").

The difficulty with applying such an approach in concept design is that most of this information is not readily available, or is a matter of debate. Producibility analysis of the entire system with such a form is complicated. For example, how does one apply this worksheet to an airframe, as is the topic of Chapter 7? It cannot be applied to such a complex problem. Instead, it is limited to lower level elements or parts, which may or may not yet be defined in the decomposition or defined to sufficient degree in concept design that the analysis can be performed. The PAW is readily applicable in detail design but has weaknesses that limit its usefulness in concept design.

MECHANICAL
Producibility Assessment Worksheet

Assessment Candidate ______________________

Production Method (PM) ______________________

1. ______________________
2. ______________________
3. ______________________
4. ______________________

	Method	PM #1	PM #2	PM #3	PM #4
A1 Design					
.9 Existing/simple design					
.7 Minor redesign/increase in complexity					
.5 Major redesign/moderate increase complexity					
.3 Tech. eval. complex design/significant increase					
.1 State-of-the-art research req./highly complex					
A2 Process/method					
.9 Process is proven and technology exists					
.7 Previous experience with process					
.5 Process experience available					
.3 Process is available, but not proven yet					
.1 No experience with process, needs r&d					
A3 Materials (availability/machinability)					
.9 Readily available/aluminum alloys					
.7 1-3 month order/ferrous alloys					
.5 3-9 month order/stainless steels					
.3 9-18 month order/non-metallic (SMC, etc.)					
.1 18-36 month order/new r&d material					
A4 Tooling					
.9 Simple fixture					
.7 Minor fixturing					
.5 Moderate fixturing					
.3 Significant fixturing					
.1 Dedicated fixturing					
A5 Design to cost (DTC)					
.9 Budget not exceeded					
.7 Exceeds 1-5% in DTC					
.5 Exceeds 5-20% in DTC					
.3 Exceeds 20-50% in DTC					
.1 Cost DTC goals cannot be achieved >50%					

Producibility Assessment Ratings PM #1 ______ PM #2 ______ PM #3 ______ PM #4 ______

For each Method $\frac{(A1 + A2 + A3 + A4 + A5)}{5}$ = Producibility Assessment Rating for that Method

Figure B-1. Producibility Assessment Worksheet [NAVSO].

The second producibility tool is statistical analysis to judge process capability against the design tolerances. This too requires a level of detail that is not available in concept design. In addition, the representation in the guidelines does not reflect the knowledge captured in chains because it does not reflect the impact that decomposition and reference frame assignment have on how end dimensions in an assembly are achieved. Simply, the analysis focuses on the nominal assembly configuration without recognition for how parts are really assembled. I have outlined the basis for chains and explained why they are a proper means for mapping the contributors to KC delivery in mechanical assemblies.

These two producibility tools are applicable only if applied in the framework of the architecture and decomposition debate that occurs in concept design. If the Chain Metrics Method (CMM) is applied first to decomposition candidates, which can be performed without a great level of detail, then a set of priorities in each candidate can be identified. The information needed for both the PAW and quantitative variation analysis could then be developed just for the highest priorities, the high integration risk integral characteristics. The PAW can be applied to elements that lie on the chains of integral characteristics, and could contribute to a more comprehensive set of metrics when added to the integration risk metrics described in Section 4.3.2.

Producibility Tools Developed by JSF

Although tools like those described above have been in use for some time and were available for use at the initiation of JSF, this program decided to take to the lead in developing a larger suite of producibility analysis tools. These tools included an open environment for linking producibility assessment tools with other information like 3D CAD data, linking cost and simulation tools, etc.

One tool, called Manufacturing Capability Requirements (MCR), was devised as an approach for linking process capabilities through elements of the WBS to the requirements they affect. This tool took the form of an information flowchart and a software tool to guide the user called the JSF Manufacturing Capability Assessment Tool Set (JMCATS). Because the information flowchart had content similar to the CMM, the software developer and I discussed the shared goals for MCR and CMM in some detail.

We found three major positives of the MCR/JMCATS approach: 1) the MCR, similar to the CMM, recognizes that the act of decomposition influences how functions are dispersed among the physical elements, 2) MCR supports qualitative and quantitative analysis, so it adapts to the level of product definition, and 3) MCR is not just a traditional "producibility analysis" tool, instead it lets many processes and capabilities be considered in the context of new technology investment, new suppliers, etc.; several interrelated strategic issues are supported.

We found two shortfalls of MCR/JMCATS : 1) it requires the team to depict the decomposition and input how requirements are delivered, i.e. it doesn't help the team with the identification of the functional-physical mapping, and 2) it allows the team to flow requirements only into single branches of the WBS, so it has limited utility for integration issues and therefore will not, in current form, assess integration risk like that I have observed in my research.

The CMM revealed and addressed both of these shortfalls. First, chains identify the mapping of function to the physical elements, and could be included in such a tool like JMCATS to show the user how different decompositions result in a different functional-physical mapping. Second, chains show how functions are dispersed among physical elements in many branches of the WBS. This can be used to improve the data structure of a tool like JMCATS to reveal integral characteristics.

The fact that JSF was pursuing an approach like MCR/JMCATS emphasizes that JSF was not only a good case study from point of view of the product. In addition to providing a highly integral product for exercising the CMM, the JPO and contractors were pushing the DOD thinking in how producibility analysis should be injected early in the development process and the type of tools needed.

Appendix C

Strategies for Assigning Reference Frames

It is valuable to depict knowledge of reference frame assignments to accurately represent the chains. The JSF keel alignment example in Chapter 4 illustrates this point by showing how different reference frame assignments alter the branch of the chain in the bay module. However, this information must be applied consistent with Principle #3 and its rules.

There are three main strategies to make reference frame assignments. First, it is possible that some assumptions about a decomposition will dictate specific reference frame proximity and assignments. There is one type that I call "natural" reference frames where boundaries between systems or modules will create natural features for joining these elements. An example is the engine-pylon mate in the C-17. The engine, by the nature of the decomposition, is made to be mated directly to the pylon at its lugs. Natural reference frames also occur where freedom, i.e. motion, is designed in. Proximity reference frames may also be a consequence of assembly strategy. Say in the JSF case that the assembly plan involves mating the modules directly to each other (as opposed to fixturing the modules relative to each other and then fastening them). In order to mate the forward module to the bay module, the reference frames for the two will have to lie in the region where the two mate. A sub-assembly far from that region could not have the module reference frame. So we may not be in a position to assign a reference frame specifically, but we know the proximity of a reference frame and therefore may be able to derive which sub-assembly or even component that would be assigned that reference frame.

The second strategy is to capture chains with generic reference frames and then systematically investigate different options, as illustrated in the keel alignment PKC. The team should have in mind a set of options for reference frames and compare their impact on the chains, following the Uniqueness and Consistency rules. If a consistent datum scheme is employed from top level assemblies down to parts, these reference frames may be the same in several lower levels of the decomposition (e.g. if a module reference frame is assigned to a component, it may be the same reference frame used for the sub-assemblies and the component).

The final strategy involves delaying some commitment to reference frame assignments by only assigning some degrees of freedom. For example, if a PKC involves only one or a few degrees of freedom, the datums that will establish the reference in the corresponding coordinates may be clear even if the full reference frame is undefined. That may allow the chains to be defined with more clarity for some PKCs while only generic chains will be captured for others. So, in the JSF case, if keel alignment just involves left to right alignment (not up and down or fore to aft), then an assignment of the left to right reference frame can be made while commitment to others can be delayed.

These three strategies allow for some detail to be injected even though the concept design environment with little detailed definition does not allow definition of the full chains.

Appendix D

A Formal Statement of the Chain Capture Procedure

This appendix introduces a formal statement of the chain capture procedure. It begins with a summary of patterns observed in chains, and then outlines an algorithm for capturing chains.

Chain Patterns

There are three major patterns in chains:

- Two end feature loop pattern: a single loop between two end features of a PKC where the loop starts at the root link and forms two branches that meet at the double-headed arrow representing the PKC.
- cascade pattern: a branch in which none of the reference frames are assigned forms a pattern where arrows point from the root link to the reference frames of all subsequent elements in the branch, to the last element containing the end feature, and to the end feature (e.g. the branch in the mid module for the JSF keel alignment PKC). In the Hierarchy Display this appears to cascade down a branch of the WBS.
- cross pattern: a branch in which one or more reference frames are assigned forms a pattern where the arrows move to and through several elements in the branch (e.g. the inlet/engine branch of the nacelle example PKC). In the Hierarchy Display this would appear as a line at the lowest level of the WBS, but the rules for this presentation force the display to indicate a cascade pattern to better reveal the shared delivery of the PKC.

Figure D-1 summarizes the content of three paths that occur when the general chain capture procedure is followed. Figure D-2 shows an abstract hierarchical notation that I will use to explain the three paths. In this notation, the WBS is shown as a hierarchy of reference frames, with circles are used to depict "end parts" - the elements at the lowest level of the decomposition that contain the end feature, where the end feature on one of these parts is somewhere on its perimeter. A circle with a reference frame attached to it represents a known reference frame assignment to that end part.

Path 1 in Figure D-1 is taken for a PKC with any number of end features that are all contained in the same part. The chain is solely at the part level and the contents are determined by the datums used in the fabrication of the part and its end features.

Path 2 is followed for PKCs with two end features in two end parts. If the root link is between parts, then the chain looks like that shown in Figure D-3a (end parts are a and b). If the root link is between higher level elements, two additional possibilities occur in each branch (the remaining steps are applied to each branch). One possibility is that the reference frame in the branch is assigned to a part. In this case the "cross pattern" occurs. The chain procedure captures links up the branch containing the reference frame, over to the branch containing the end feature, and down to the end part and end feature, as shown in Figure D-3b (in branch with end part a, branch reference frame is in part d). The other possibility is that the reference frame is unassigned, in

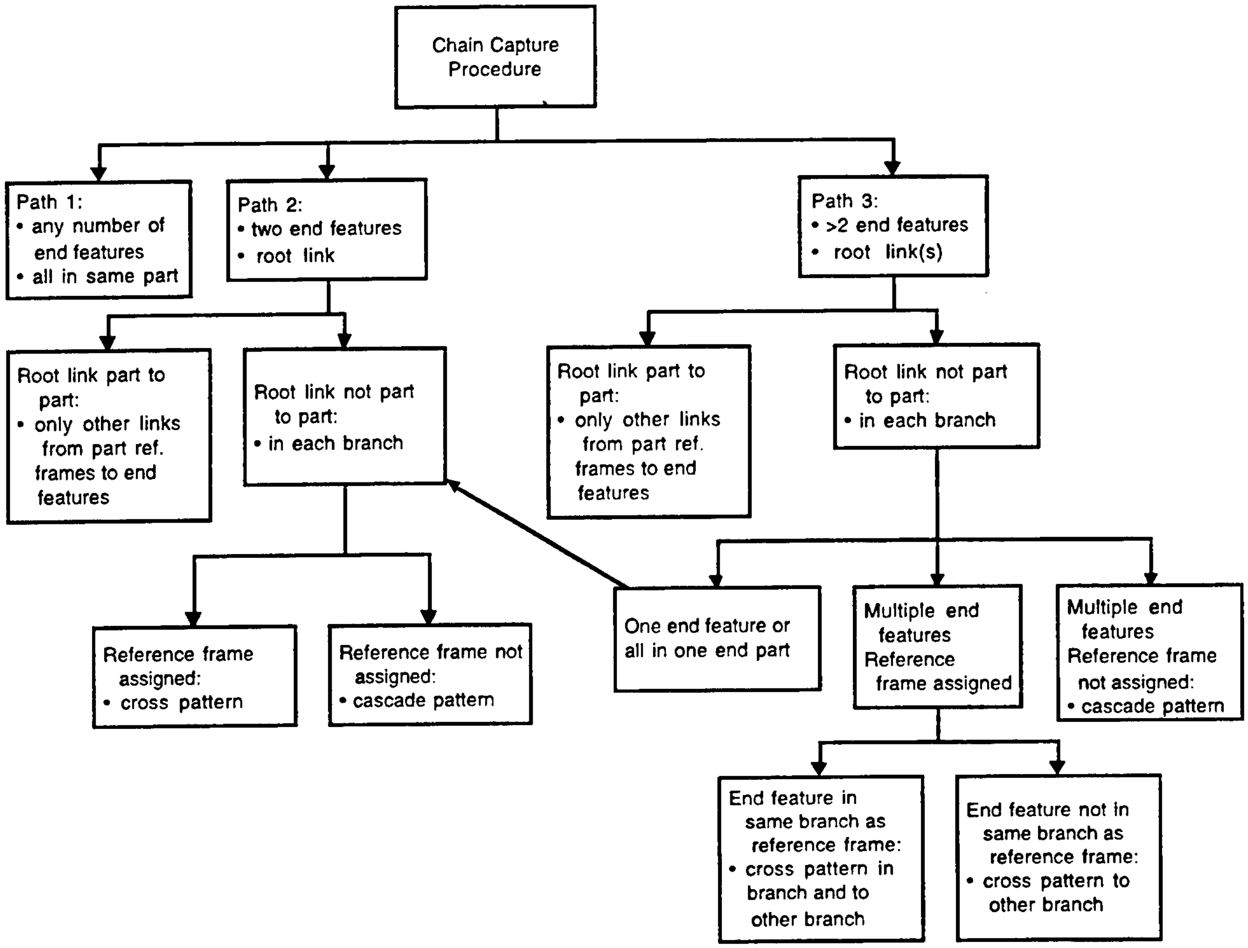

Figure D-1. Summary of the content of the chain capture procedure.

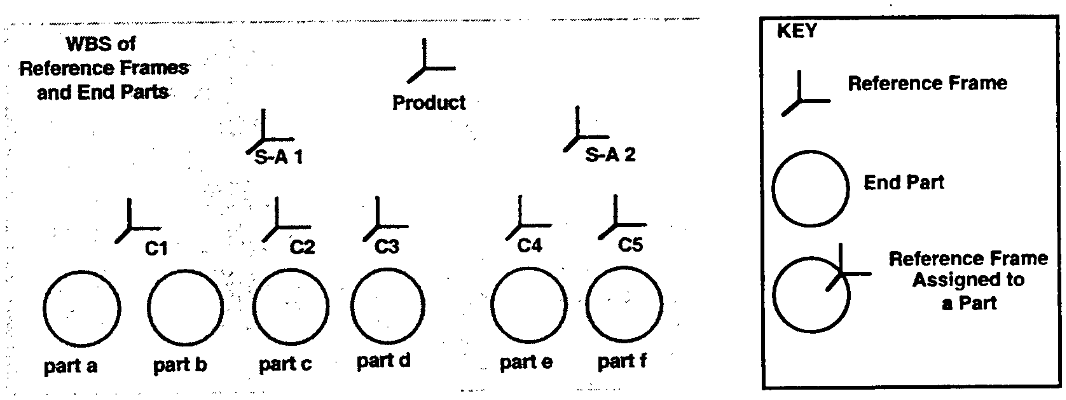

Figure D-2. Abstract notation of the WBS

which case the procedure "cascades" down the branch, reference frame to reference frame, to the end part and end feature, as shown in Figure D-3c (in branch with end part f).[1]

Path 3 is followed for PKCs with more than two end features. If the root link is between parts, then the chain looks similar to that shown in Figure D-3a, only there are more than two end

[1] Note that all three chains form a loop when there are only two end features.

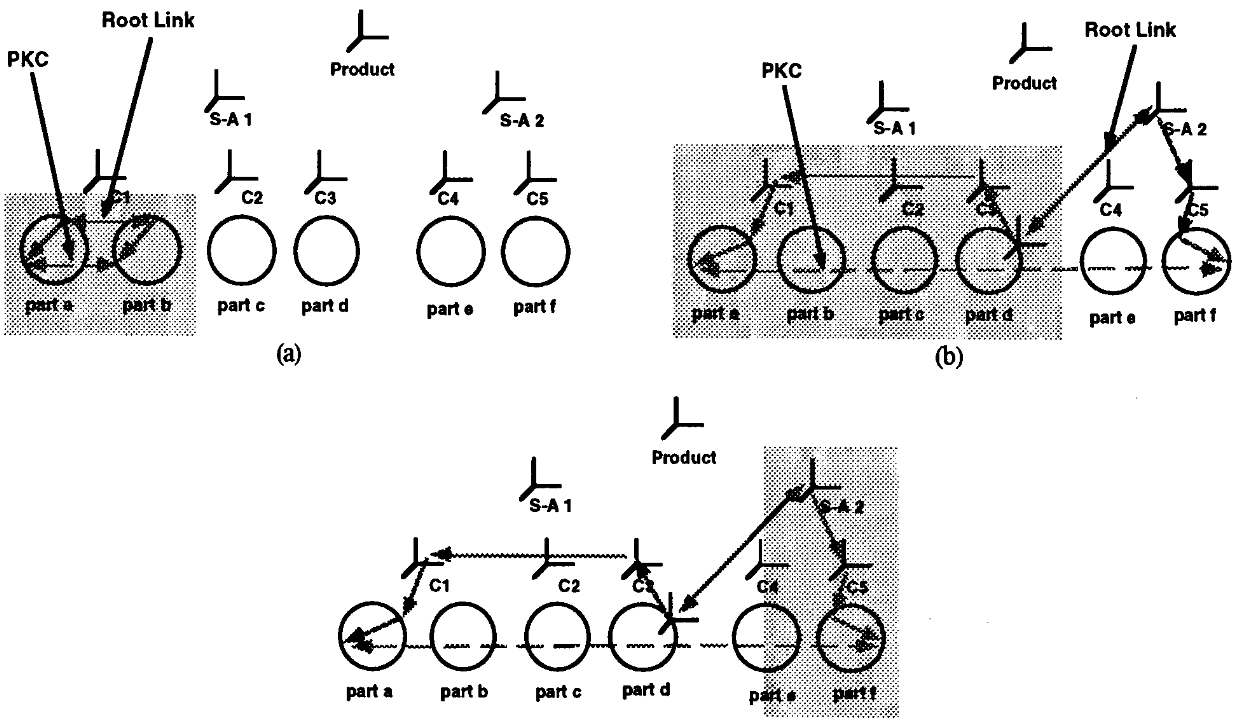

Figure D-3. (a) All end features in parts constrained at the lowest level of the WBS. (b) The "cross" pattern found when the reference frame is assigned. (c) The "cascade" pattern found when the reference frame is unassigned. Note that all three are loops.

features. If the links are between higher level elements, the additional possibilities depend on the number of end features in each branch. If one end feature is in the branch or the entire sub-set is in one end part, the remaining steps are the same those described in path 2. If there are two or more end features in the branch in two or more end parts, then there are two possibilities if the reference frame in the branch is assigned to a part. One, the reference frame is in the same branch as an end feature, in which case the portion of the chain resembles that in Figure D-4a (cascade and cross patterns, branch has end parts a, c, and d, reference frame is in d). Two, the reference frame is in a branch without an end feature, and the portion of the chain resembles that shown in Figure D-4b (just cross patterns, branch has end parts a, and c, reference frame is in d). If the reference frame is unassigned in a branch containing multiple end features, the procedure cascades down the branch to the level that the sub-set of end features is fully constrained, then splits to the branches each containing subsequent sub-sets of end features. This is shown in Figure D-4c (end parts a, b, and c).

Chain Capture Procedure

Assume the decomposition is X levels, with the top level number 1. For each PKC the following is needed:

- Y: the number of end features
- A: the level at which the end features are fully constrained, governed by equation 4-1
- B1, B2,...Bi: identification of the different branches below level A that contain a sub-set of the end features, governed by equation 4-2

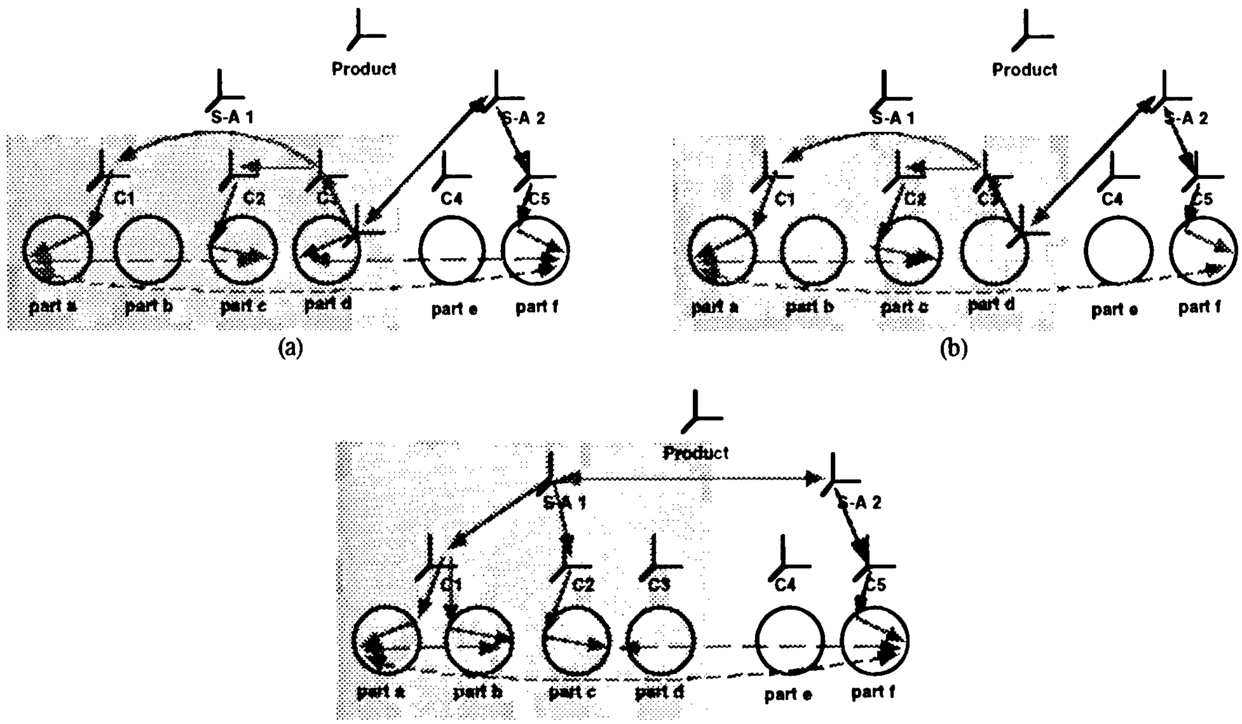

Figure D-4. Patterns when one branch contains a sub-set of the end features: (a) an end feature in the same branch in which the reference frame is assigned. (b) no end feature in the same branch in which the reference frame is assigned, and (c) The "cascade" pattern found when the reference frame is unassigned.

- C1, C2,...Ci: number of end features in each sub-set, governed by equation 4-3
- D1, D2,...Di: the level of decomposition in each branch, governed by equation 4-4
- E1, E2,...Ei: the level in each branch B that the sub-set of end features is delivered, has the same relationship with A and X as D
- F1, F2,...Fi: the number of branches end features in each branch, governed by equation 4-5

$$1 \leq A \leq X \qquad \text{(D-1)}$$

$$i \leq Y \qquad \text{(D-2)}$$

$$\sum_i Ci = Y \qquad \text{(D-3)}$$

$$A \leq D \leq X \qquad \text{(D-4)}$$

$$Fi \leq Ci \qquad \text{(D-5)}$$

The following steps capture the chain for the PKC:

- if A=X and X is the level of parts, the end features are in the same end part, the chain is simply the relative location of the end features relative to the part datums used in fabrication. Continue with the next PKC. This is path 1 in Figure D-1.

- if Y=2, and A is above the level of parts:
  - enter the root link at level A+1 (or at the next populated level)[2]
  - if A+1=X and X is the level of parts, then the root link is from end part to end part; indicate a link in each end part from its reference frame to the end feature, and the chain is complete. Continue with the next PKC.
  - otherwise:
    - in B1:
      - determine D1
      - if the reference frame at level A+1 is assigned to an element at a level between A+1 and D1
        - determine level E1 where reference frame for level A+1 is constrained relative to the end feature
        - chain up by adding a link from the reference frame for level A+1 to the reference frame at the next level, continuing to level E1+1 (skipping any unpopulated levels)
        - link from the reference frame at E1+1 in the branch containing the reference frame for level A+1 to the reference frame at E1+1 to the branch containing the end feature
        - continue the chain by adding a link between each reference frame and the next one down in the decomposition from level E1+1 to D1 (skipping any unpopulated levels)
        - complete the chain with the final two links
          - pass the chain from the D1 reference frame to the end part, representing the location of the end part locators relative to the D1 reference frame, and
          - pass it through the end part representing the end feature relative to the end part locators.
      - otherwise the A+1 reference frame is unassigned, so
        - continue the chain by adding a link between each reference frame and the next one down in the decomposition from level A+1 to D1 (skipping any unpopulated levels)
        - complete the chain with the final two links
          - pass the chain from the D1 reference frame to the end part, representing the location of the end part locators relative to the D1 reference frame, and
          - pass it through the end part representing the end feature relative to the end part locators.
    - in B2 do the same
- if Y>2, and A is above the level of parts:
  - if A+1=X and X is the level of parts, then capture links among the end parts;
    - in each end part Bi:

[2] In some branches of the tree there may be, for example, a system but no modules, only sub-assemblies; in this branch the module level is unpopulated and the sub-assembly level is the next populated level.

        - if Ci=1, indicate a link in the end part from its reference frame to the end feature.
        - if Ci>1, indicate a link from the end part reference frame to each end feature in the sub-set
- otherwise
    - in each branch Bi
        - determine Di
        - if Ci=1 or if Ci>1 but all are in one end part
            - follow the options for the case above for one end feature in a branch
        - otherwise there are two or more end features in the branch
            - determine Ei
            - if the reference frame at level A+1 is assigned to an element at a level between A+1 and D1
                - if the reference frame is in the same branch as all the end features
                    - if Ei=A+1 then all the end features are in the same element
                        - capture a link from the reference frame of the element containing the reference frame at A+1 to all other elements containing end features
                        - capture links to and through each end part
                    - otherwise the end features and A+1 reference frame are all constrained at a level above
                        - chain up by adding a link from the reference frame for level A+1 to the reference frame at the next level, continuing to level Ei+1 (skipping any unpopulated levels)
                        - link from the reference frame at Ei+1 in the branch containing the reference frame for level A+1 to the reference frames at Ei+1 to the branches containing each end feature
                        - continue the chain by adding a link between each reference frame and the next one down in the decomposition from level Ei+1 to Di in each branch containing an end feature (skipping any unpopulated levels)
                        - complete each branch of the chain with the final two links (including the one containing the A+1 reference frame)
                            - pass the chain from the Di reference frame to the end part, representing the location of the end part locators relative to the Di reference frame, and
                            - pass it through the end part representing the end feature relative to the end part locators.
                - otherwise the A+1 reference frame is in a different branch than the end features

            - chain up by adding a link from the reference frame for level A+1 to the reference frame at the next level, continuing to level Ei+1 (skipping any unpopulated levels)
            - continue in the same manner as the case where the A+1 reference frame is in the same branch, but do not include a branch to an end feature in the branch containing the A+1 reference frame
        - otherwise the A+1 reference frame is unassigned
            - continue the chain by adding a link between each reference frame and the next one down in the decomposition from level A+1 to Ei (skipping any unpopulated levels)
            - determine Fi
            - and continue the chain in each branch Fi following rules similar to those for multiple end features in each Fi or for single end features in each Fi
    - repeat for each branch

Return now to the hierarchy in Figure D-2. In this case X=4 (three tiers and the level of parts).

For the PKC in Figure D-3a:

- Y=2
- A=3
- because A+1=X, the first link is between the two end parts a and b and there is a link in each end part

For the PKC in Figure D-4b, with end parts a, c, and f:

- Y=3
- A=1
- There are two branches, B1 contains end parts a and c, B2 contains end part f
- C1=2, C2=1
- D1=D2=4
- E1=2, E2=n/a
- F1=2
- In B1, the reference frame is assigned to a different branch than those containing end features, so the procedure captures a chain that climbs up to level 3, crosses over to the two branches containing end features, and down to the end parts.
- In B2, there is one end feature and no assigned reference frames, so the pattern cascades down to the end feature from level 2.

Appendix E

Additional Information for the 767 Horizontal Stabilizer Example

This appendix provides backup information for the 767 horizontal stabilizer example. Three topics are covered: assembly of the right stabilizer, the remaining KCs not discussed in Chapter 5, and the features used in the feature-based process.

Right Stabilizer Assembly Process

1. The FTE is located into the fixture at the pivot point which sets x, y, and z, on the elevator line at several points, at the outboard end (the assembly is overconstrained, see Figure E-1)
2. The FTB is located to two pins and four surfaces (one of which is on the end fitting) along the Forward Spar (see Figure E-1)
3. Each rib is put in place between the FTB and FTE, drilled and riveted
4. The lower skin assembly is placed in the jig by sliding the assembly from outboard to inboard until the plus chord is flush with and clamped to the FTB and FTE end fittings while evenly spacing the gap between the skins and FTB/FTE skins using spacers (note that both alignments do not always come out right, as described as the conflict between PKCs 1 and 2), and clamping the skins to the spars. The plus chord is always clamped to the aft end fitting and the gap is set on the inboard end between the FTB skin and upper skin, even if the other alignments are not achieved.
5. The upper skin assembly is placed in the jig and drilled in the same manner using a template at its interface with the spars. The lower skin is reloaded. The rib at the inboard end is placed in at this time and drilled through the plus chords and end fittings. The upper skin assembly is removed.
6. The lower skin assembly is riveted.
7. The upper skin assembly, with aft skin removed, is riveted.
8. The aft skin is riveted.

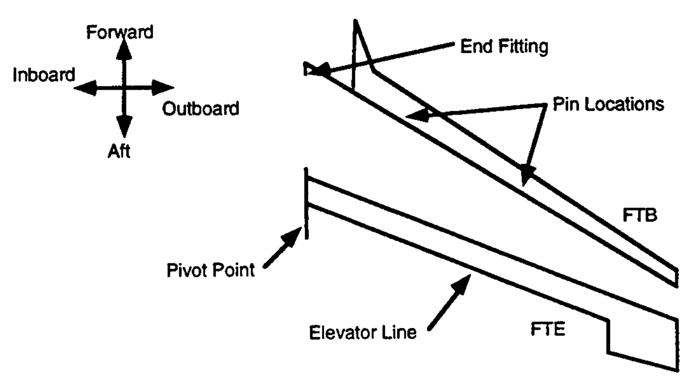

Figure E-1. Loading of the FTE and FTB starts the assembly of the right stabilizer.

Remaining KCs

Blade Seal KC

One PKC for the blade seal KC results from the decomposition. The blade seal holes must be located properly in x (inboard-outboard) relative to the centerline of the fuselage, shown in Figure E-2a. Note that for this KC there is a contribution both in the stabilizer and in the fuselage, since each will vary from nominal from their attachment at the horizontal stabilizer pivot points. Therefore, one PKC (in each stabilizer) results from the blade seal KC:

PKC #4: alignment of the blade seal holes relative to the stabilizer center line.

Figure E-2b shows a chain representation of how PKC #4 is delivered. Here only the branch in the right stabilizer is shown, as another branch would be found in the fuselage. The position in outboard of the right stabilizer is set by the hinge line location at final assembly, but at the pivot point in the right stabilizer assembly. This is a datum shift between the module level and the sub-assembly level. One interaction between the FTE and Upper Skin affects this PKC, the same one that determines PKC #1.

Assembly KCs

Two other alignment issues were considered in the analysis to represent features whose variation complicates the assembly process. First the plus chord position in fore-aft affects whether the scallops on the center box side of the plus chord align properly with the stringers in the center box (which are on the same lines as the inboard ends of the stringers in the left/right stabilizer. Currently several fasteners are left out of the center box and installed at final assembly after the stringers are moved onto the proper plus chord scallop, similar to how the stringers are positioned by hand to the scallops in the current skin process described by Cunningham et al [1996]. Second, the gap between the plus chord and splice plates affects the time needed to move the stabilizers in position relative to the center box at final assembly. The consistency of

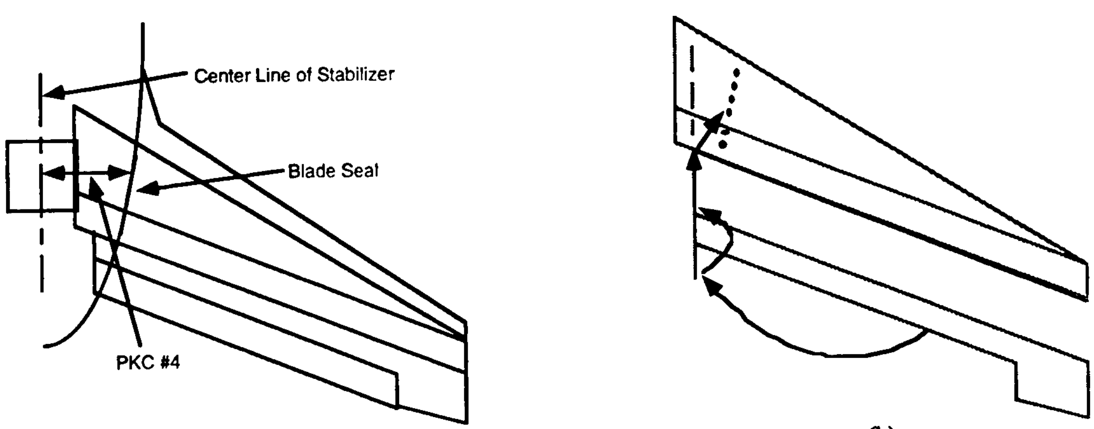

Figure E-2. (a) Blade seal position relative to the stabilizer and aft fuselage center line and (b) portion of chain for PKC #4 that lies in the left/right stabilizer.

this gap, and the contour, is also an issue for assembly. This is time consuming and was considered an issue to be evaluated.

Figure E-3 shows the chain for plus chord position fore/aft relative to the center box stringers. Recall the center box is located in y relative to the aft end fittings, to which it is placed in direct contact. Therefore the chain initiates at that point, then traverses to the skin gap between the FTE skin and aft skin which sets the Upper Skin in y relative to the FTE, and finally from the aft skin aft edge to the plus chord.

Assembly KCs are denoted in all elements of the WBS as relationships identified in chains that affect the delivery of the PKCs. Four AKCs were identified for the Upper Skin (as discussed in Cunningham et al [1996]):

AKC #1: Plus chord angle in z relative to aft skin aft edge - accounts for PKC #1 and PKC #2.

AKC #2: Plus chord position in y relative to the aft edge of the aft skin - final link in chain of Figure E-3.

AKC #3: Inboard sandwich of the splice plates, skins, and plus chord (spacing and contour).

AKC #4: Blade seal hole locations in x relative to plus chord web - accounts for PKC #4, final link in chain of Figure E-2b, note there is a discrepancy between this AKC and AKC #4 in [Cunningham et al 1996]

Feature-based Process

The following describes the set of features shown in Figure 5-49:

- Forward Skin -
  1. slots machined along the aft edge (parallel to that edge) to integrate with holes machined on stringer 3,
  2. slots machined elsewhere along the length of the skin to integrate with holes on other stringers, and
  3. 1 slot and 4 oversized holes to mate with splice plates and plus chord,[3] and a fore/aft aligned slot to mate with inboard end of stringer 3.

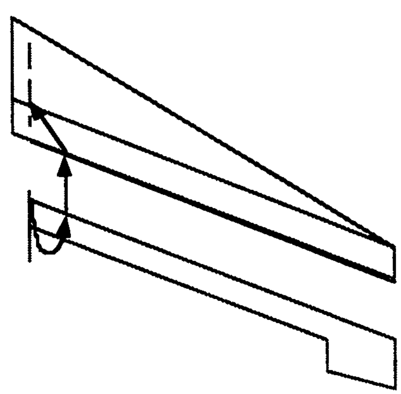

Figure E-3. Chain in left/right stabilizer that sets the plus chord position in y relative to the center box stringers.

[3] The oversized holes are not used for location, just to clamp the plus chord, skins, and splice plates with temporary fasteners.

- Aft Skin -
  1. slots machined along the forward edge to integrate with holes machined on stringer 3,
  2. slots machined elsewhere along the length of the skin to integrate with holes on other stringers, and
  3. 1 precise diameter hole and 1 oversized hole to mate with aft splice plate and plus chord, and a fore/aft aligned slot to mate with inboard end of stringer 3.
- Stringer 3 -
  4. holes machined along length to attach to both skins.
- Other stringers (not shown in Fig. 5-10) - holes machined along each stringer to attach to skins and one hole machined on each to mate with plus chord
- Plus Chord - one hole to mate with each stringer (not visible in Fig. 5-10), and
  5. seven holes to mate with skins and splice plates.
- Splice Plates -
  6. one hole and two slots on the aft splice plate, and
  7. two slots on each of the other two splice plates.

Appendix F

Design Structure Matrices for Selected Design Approaches

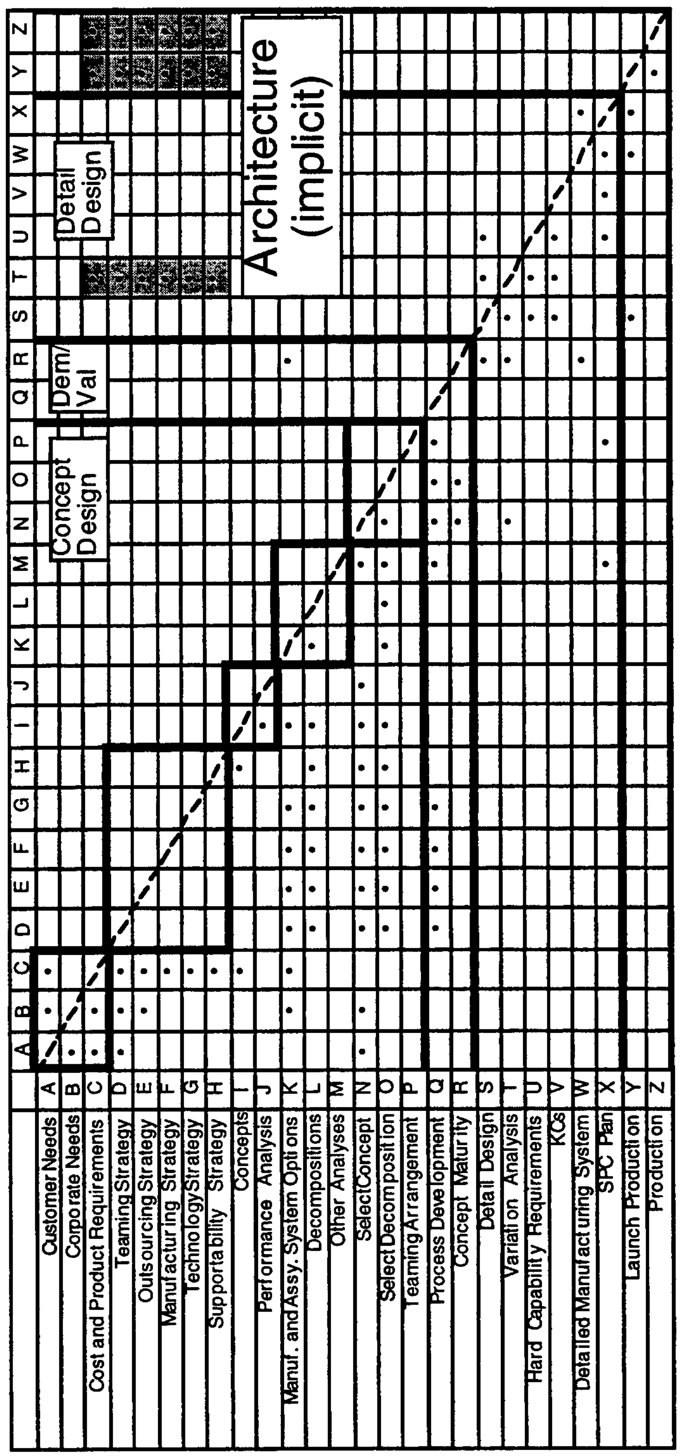

Figure F-1. DSM showing how architecture insight is attained late in the process when the CMM is not present.

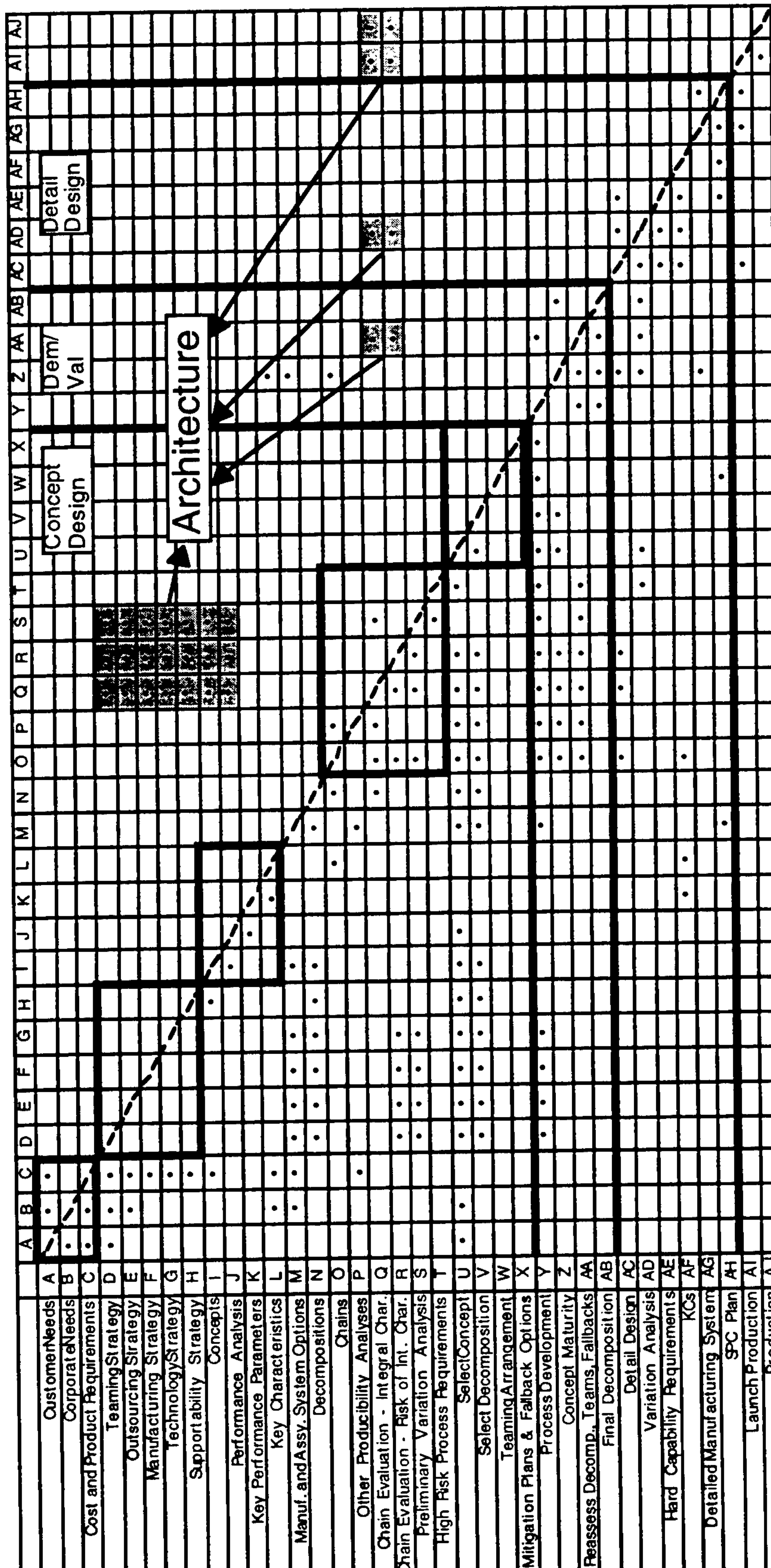

Figure F-2. Full DSM showing how architecture insight is attained with the CMM.

Appendix G

Questionnaire on the Research Submitted to LMTAS JSF IPT Members

2. Concept

2a. Chains are intended to differentiate among candidate decompositions by indicating integral characteristics and risk. In what specific ways did you find the chains concept helpful to you in describing and understanding the different module break candidates?

2b. Chains are intended to build a system perspective of quality that can be shared at all levels of the IPT. In what specific ways do chains improve the system view of quality?

2c. Chains are intended to communicate in a non-technical format to the broader IPT technical information about how dimensional control is achieved. Do chains capture meaningful technical information? And, can this information be shared among the team? How?

2d. Can you construct a scenario (or scenarios) where the chain representation would enhance the communication among different members of the IPT?

2e. Has the chain case study added insight into the selected concept, teaming arrangement, and processes in terms of its KCs, integral characteristics, risk, priorities, etc.? Please explain.

2f. Would the presence of chains have altered the priorities of the producibility analyses conducted earlier (pre-proposal for CDA) in this (or another past) program?

If not, would chains be included in this phase in future programs, or after concept selection? Why or why not?

Do you feel chains are something that is missing from concept design altogether, or is it there but underemphasized/underutitilized?

Should chain documentation/analysis take priority over other producibility activities? Which? (note this question is slightly different that the first in this list numbered '1f'. The first asks 'would it' and this asks 'should it')

2g. Would the presence of chains have altered the priorities established for manufacturing/assembly technology investment when those were debated late in Concept Exploration or as those activities have proceeded in early CDA? How?

2h. What is the most valuable kind of information that the chains method is capable of providing? Is that information valuable enough to justify the effort of doing a chain analysis? If not, can the method be improved enough to overcome these problems? How?

3. Method

3a. Do you feel you can draw a chain for any assembly process with which you are familiar (one from your experience with known parts, locators, etc.)?

Have you tried?
(optional) sketch one here or on the separate blank worksheet at the end of this questionnaire

3b. Do you feel you can draw a chain for a decomposition with limited definition of parts and locators?

Have you tried?
(optional) sketch one here or on the separate blank worksheet at the end of this questionnaire

3c. What do you think is the minimum information that needs to be available to you before you can make productive use of the chain method during concept design?

full 3D solid models of all major assemblies?

sketches showing major subsystems, aircraft rough surface outlines, and load bearing structure?

a decomposition to what level?

locators that accompany a candidate decomposition?

etc. (fill in)?

3d. Can you relate chains to the roles suppliers play in delivering Key Characteristics? Is this approach more structured than the current flowdown method?

Is it applicable earlier than the current flowdown method?

3e. Can you relate chains to critical path in production? Would a chain analysis of a concept affect critical path assumptions and estimation for that concept compared to the current flowdown method? If yes, how?

3f. Can you relate chains to technologies that affect the delivery of Key Characteristics? Does a chain analysis of a concept help you to identify and set priorities among the various manufacturing technology development and characterization efforts?

3g. Can you apply all the metrics included in the chain method? If not, which can you and which can't you and why?

3h. Are there other metrics of chains that should be included but are not in the current proposed set?

3i. Please comment on how the method can fit into the current time and resource constraints faced by the IPT during concept design. For example, could it displace other baseline activities because it does them better or because it creates more valuable information currently unavailable or undocumented/unutilized?

4. Effectiveness

4a. Chains are intended to stimulate thinking about critical downstream integration issues much earlier in development than people generally believe is possible, given the lack of detailed design definition in concept design. Is the signal/noise ratio of chains high enough to justify its use? That is, does it provide information of great enough value given the uncertainty of the data?

4b. Chains are intended to strengthen producibility input to concept design. Does the method relate chains to producibility and integration issues?

Does the method do so than current method? In what specific ways?

4c. Chains are intended to inject a scientific basis to the concept design producibility debate. Does the method relate chains to a scientific basis?

4d. Chains are intended to provide broader and more meaningful metrics of product architecture into concept exploration. Does the method relate chains to meaningful metrics about product architecture?

4e. Chains are intended to lead to quantitative variation analysis earlier than seen in current processes. Though not demonstrated in this case study, do chains have the potential to guide earlier quantitative variation analysis? Would that variation analysis fit with the configuration process?

5. Implementation

5a. Chains are intended for communication at multiple levels in the IPT and among teams working on different versions of the product (AAD, PWSC, etc.). What roles on the IPT would need to be defined to make this happen successfully?

What tools to perform the method need to be developed to make this happen successfully?

What training needs to be developed for the team to execute the method?

5b. Chains are intended to be a living element in product development. Can chains communicate information that provides traceability from early decisions to downstream development steps? How?

5c. Chains are intended to aid in IPT communication about the product, process, supply chain and risk. What role can chains play in communicating about these issues among team members and suppliers?

with the program office, formally (proposal) or informally?

5d. Do you think (if yes, mention what form of display) chains will end up in some way in how you package information about your design/KCs/process/supply chain in your EMD proposal?

in your meetings with outside team members and suppliers?

on the wall of the room housing your IPT in Ft Worth?

on the production floor 10 years from now?

5e. What other barriers are there to implementing a chain-driven producibility analysis in concept development?

6. Future Work

6a. What are some immediate next steps for chain development (e.g. automated tools, a raw architecture score, CAD tools, etc.)

6b. What representations of chains would improve communication of the idea in the IPT?

6c. To what other systems besides airframe (e.g. fuels, propulsion, avionics) is the concept migratable?

not migratable?